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INVESTIGATION OF TEST METHODS, MATERIAL PROPERTIES, AND PROCESSES FOR SOLAR CELL ENCAPSULANTS

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ENCAPSULATION TASK OF THE LOW-COST SILICON SOLAR ARRAY PROJECT

The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

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I. SUMMARY

Springborn Laboratories is engaged in a study of evaluating potentially useful encapsulating materials for the Low-Cost Silicon Solar Array project (LSA) funded by DOE. The goal of this program is to identify, evaluate, and recommend encapsulant materials and processes for the production of cost-effective, long-life solar cell modules.

Due to the continuing commercial interest in the EVA lamination pottant, some revised studies were conducted with respect to the time/temperature cure requirements for successful use of this compound. The times needed to produce successful gel contents were redetermined at a variety of temperatures and these results were related to the peroxide half-life temperature curve.

Formulation of the butyl acrylate syrup/casting pottant was completed and is now ready for the first stage of industrial evaluation. The formulation contains an ultraviolet stabilizer system and may be cured with an initiator that, unlike former selections, presents no shipping or handling hazards to the user. The catalyzed syrup is stable at room temperature and has a pot life of at least an eight hour (one shift) period of time. The syrup cures to a transparent rubber in 18 minutes at a temperature of 60°C.

A second liquid casting system was also explored during this time and is based on aliphatic urethane chemistry. This formulation is a prototype solar cell encapsulant manufactured by Development Associates, Inc., N. Kingstown, R.I. and is available in pilot plant quantities. This urethane is characterized by high transparency, low mixed viscosity, fast cure time and surprising lack of moisture sensitivity that has given trouble with previous urethane compositions. This material is produced with an ultraviolet stabilizer system already blended in and additionally has a history of use in outdoor applications.

The formulation of the ethylene/methyl acrylate lamination pottant was also completed during this period of time. This compound is the alternative pottant to EVA and is similarly produced as an extruded sheet that is wound into rolls. Experiments were conducted to select the most appropriate base resin for this compound and generate a first-cut formulation suitable for

industrial evaluation purposes. The large scale extrusion conditions were determined and a 250 pound quantity was produced as a film of 30 inch width and 0.02 inch gauge. This resin is inherently non-blocking; consequently no release paper was used to separate the plies. Experimental modules were prepared to verify performance and the cure profile was determined at a variety of times and temperatures.

A survey was made of elastomers for use as gaskets for the photovoltaic module. Of the wide variety of materials examined EPDM offered the optimum combination of low compression set and low cost. The preference for EPDM is supported by its long history of use as an automobile gasket. A number of industrial manufacturers were identified and a wide range of products are available including both standard and custom-made profiles.

The commercial availability of materials that would be useful for sealants between the edge of the module and the gasket was investigated. Butyl sealants have the best combination of physical properties, low cost and a well-documented history of performance. A large number of suppliers were contacted and many commercial formulations found, however a preferred composition has not yet been identified.

The effectiveness of a new primer for EVA was determined during this period. This formulation was similar to the silane coupling agent used in past experimentation but was modified with a peroxide to enhance the chemical activity. Excellent bond strengths were obtained to glass, and mild steel that were resistant to immersion in boiling water. EVA to low iron glass gave an average bond strength of 35 lbs per inch of width. This new primer was also evaluated for the corrosion protection that could be provided to metal surfaces when primed and encapsulated in EVA. Specimens exposed to long term salt spray were not as adequately protected as they had been with the previous formulation. Mild and galvanized steel showed distinct signs of attack where previously none had been observed. The resistance to corrosion appears to be related to chemical mechanisms other than just bond strength at the surface.

Differential thermal analysis (DTA) was used for the examination of thermal stability in some of the pottant compounds of current interest. This method was useful in determining the temperatures at which oxidation

or pyrolysis reactions resulted in degradation of the polymers. All the candidate pottants showed degradation temperatures of over 200°C. Although encouraging, it is not known exactly how these results relate to long term thermal aging accumulated in field operations.

An experimental program was started to determine the effectiveness of soil resistant coatings. These coatings are intended to be surface treatments applied to the sunlit side of solar modules and function to prevent the tenacious adhesion of soil to the surface, aid in its removal, and consequently keep the power output high. These treatments have been applied to "Sunadex" glass, Tedlar and oriented acrylic film. The treatments are based on silicone, acrylic, and fluorosilane chemistries. Test specimens are being exposed to outdoor soiling conditions with subsequent testing for power loss using a standard cell device. Testing is done at monthly intervals and a record of the weather patterns is also maintained to observe the effect of rainfall. To date the best treatment appears to be based on the fluorosilane treatment.

Hardboard (wood) based materials hold the promise of being the most cost effective substrate materials due to their inherently low cost and high flexural modulus. They have an engineering deficiency, however, due to their prohibitive hygroscopic expansion coefficient. Dryout during vacuum bag lamination and subsequent moisture regain causes large expansions and contractions of these materials and results in cell breakage when they are used as substrates in solar cell modules.

Experiments were conducted to determine if these hardboards could be "passivated" through the use of occlusive coatings. Aluminum foil and polymer films were used in conjunction with a variety of adhesives for this purpose. Coated/encapsulated hardboards were run through the standard vacuum bag cycle to simulate a fabrication process. In all cases the trial substrates failed due to the severity of the conditions. Coated hardboards may, however, be perfectly acceptable for use with the low temperature liquid casting methods that do not result in destructive gassing of the wood. The ability of these coatings to damp outdoor humidity swings will also be investigated in future work.

The optimization of encapsulation materials will receive emphasis in future work. Experiments will be directed towards the selection of UV stabilizers, antioxidants, primers, crosslinking agents, cure schedules, etc. for the technical completion of the potting compounds. High reliability and cost effective coatings for wood and steel substrates will also be identified and evaluated by outdoor and accelerated exposure testing. Experimental methods for the determination and correlation of outdoor service life and degradation rates will be studied to verify and predict the performance of encapsulation materials.

II. INTRODUCTION

The goal of this program is to identify and evaluate encapsulation materials and processes for the protection of silicon solar cells for service in a terrestrial environment.

Encapsulation systems are being investigated consistent with the DOE objectives of achieving a photovoltaic flat-plate module or concentrator array at a manufactured cost of \$0.70 per peak watt ($\$70/\text{m}^2$) (1980 dollars). The project is aimed at establishing the industrial capability to produce solar modules within the required cost goals by the year 1986.

To insure high reliability and long-term performance, the functional components of the solar cell module must be adequately protected from the environment by some encapsulation technique. The potentially harmful elements to module functioning include moisture, ultraviolet radiation, heat build-up, thermal excursions, dust, hail, and atmospheric pollutants. Additionally, the encapsulation system must provide mechanical support for the cells and corrosion protection for the electrical components.

Module design must be based on the use of appropriate construction materials and design parameters necessary to meet the field operating requirements, and to maximize cost/performance.

Assuming a module efficiency of ten percent, which is equivalent to a power output of 100 watts per m^2 in midday sunlight, the capital cost of the modules may be calculated to be \$70.00 per m^2 . Out of this cost goal only 20 percent is available for encapsulation due to the high cost of the cells, interconnects and other related components. The encapsulation cost allocation^(a) may then be stated as \$14.00 per m^2 which includes all coatings, pottants, and mechanical supports for the solar cells.

Assuming the flat plate collector to be the most efficient design, photovoltaic modules are composed of seven basic construction elements. These elements are (a) outer covers; (b) structural and transparent superstrate materials; (c) pottants; (d) substrates; (e) back covers; (f) edge seals and gasket compounds, and (g) primers. Current investigations are concerned with identifying and utilizing materials or combinations of materials for use as each of these elements.

(a) JPL Document 5101-68

The former cost allocation for encapsulation materials, was \$2.50/ m^2 ($\$0.25/\text{ft}^2$) in 1975 dollars, or \$3.50/ m^2 ($\$0.35/\text{ft}^2$) in 1980 dollars. The current cost allocation of \$14/ m^2 is an aggregate allocation for all encapsulation materials including an edge seal and gasket.

Extensive surveys have been conducted into many classes of materials in order to identify a compound or class of compounds optimum for use as each construction element.

The results of these surveys have also been useful in generating first-cut cost allocations for each construction element, which are estimated to be as follows(1930 dollars):

Construction Elements	Approximate Cost Allocation ^(a) (\$/m ²)
. Substrate/Superstrate (Load Bearing Component)	7.00
. Pottant	1.75
. Primer	0.50
. Outer Cover	1.50
. Back Cover	1.50
. Edge Seal & Gasket	1.85

(a) Allocation for combination of construction elements: \$14/m².

From the previous work, it became possible to identify a small number of materials which had the highest potential as candidate low cost encapsulation materials. The following chart shows the materials of current interest and their anticipated functions:

Status of Encapsulation Materials

- | | |
|---|------------------------------------|
| 1. Surface materials and modification | Under development |
| 2. Top covers
(with UV screening property) | |
| a. Glass | Available |
| b. Tedlar X00 BG 30 UT | Available (duPont) |
| c. X-22417 Acrylic film | Available (3M Corp.) |
| 3. Pottants | |
| a. Ethylene Vinyl Acetate | Available (Springborn) |
| b. Ethylene Methyl Acrylate | Available (Springborn) |
| c. Aliphatic Polyether Urethane | Available (Development Associates) |
| d. Poly Butyl Acrylate | Available (Springborn) |

- | | |
|---|--|
| 4. Electrical and mechanical spacer | |
| a. Non-woven glass mats | Available (Crane Co.) |
| 5. Substrate panels | |
| a. Hardboards | Available (Masonite, "Super-Dorlux", Laurel 200, Ukiah Standard Hardboard) |
| b. Strandboard | Under development (Potlatch Corporation) |
| c. Glass-reinforced concrete | Under development (MB Associates) |
| d. Mild steel (incl. galvanized and enameled) | Available |
| 6. Back covers | |
| a. Aluminum foils and polymer laminates | Available |
| b. Tedlar, Mylar, Korad (polymer films) | Available (DuPont, Excell, 3M) |
| c. Pigmented ethylene vinyl acetate | Available (Springborn) |
| d. Others | Under development |
| 7. Gaskets | |
| a. EPDM (standard or custom profiles) | Available (Pawling Rubber Company, others) |
| 8. Sealants | |
| a. "Tape" sealants | Available (Tremco, Pecora, 3 M) |
| b. Gannable sealants | Available (Tremco, 3M, others) |

In addition to materials, two encapsulation processes are being investigated:

- (1) Vacuum bag lamination
- (2) Liquid casting

The suitability of these processes for automation is also being investigated; however, the selection of a process is almost exclusively dependent on the processing properties of the pottant. This interrelationship may have a significant influence on the eventual selection of pottant materials.

Recent efforts have emphasized the identification and development of pottting compounds. Pottants are materials which provide a number of functions, but primarily serve as a buffer between the cell and the surrounding environment. The pottant must provide a mechanical or impact barrier around the cell to prevent breakage, must provide a barrier to water which would degrade the electrical output, must serve as a barrier to conditions that cause corrosion of the cell metallization and interconnect structure, and must serve as an optical coupling medium to provide maximum light transmission to the cell surface and optimize power output.

This report presents the results of the past year which has been directed at the continuing development and testing of pottants and other components.

The topics covered in this report are as follows:

(1) Due to the current interest in the EVA pottant compound that has been produced at Springborn Laboratories, additional studies were conducted to confirm the cure behavior and the time/temperature requirements resulting in acceptable levels of gel content (measure of cure). A time/temperature gel content table was developed and a revised cure curve prepared to assist manufacturers with processing requirements. This curve relates well to the half-life decomposition curve of the peroxide curing agent.

(2) Ethylene/methyl acrylate base resins were explored for suitability in producing a compound for industrial evaluation purposes. This compound contains an antioxidant and a synergistic combination of ultraviolet stabilizers to extend its service life under outdoor exposure conditions. Peroxides used to cure the resin were also screened and a good first candidate was selected. The extrusion and processing conditions of this film lamination pottant were determined using a 2 1/2 inch pilot plant extruder and material was prepared for industrial evaluation.

(3) The development and final formulation of the butyl acrylate syrup/casting pottant. Emphasis was placed on developing a system with long pot life, room temperature stability and rapid cure at reasonably low (50°-60°C) temperatures. Low hazard initiators were evaluated for these characteristics without presenting the danger of violent decomposition, fire, and the necessity for refrigerated storage required with previously selected peroxides. Time/temperature cure requirements were determined for completed formulations prepared with ultraviolet stabilizers.

(4) A commercial source of a UV stabilized polyurethane was identified and a prototype formulation evaluated. This material is a two part liquid syrup system intended for the liquid casting method of encapsulation. The current formulation is designated Z-2211 and has the advantages of exceptionally high

transparency, very low mixed viscosity, rapid cure time and a history of successful use in an outdoor application.

(5) Gasket compounds were explored in terms of generic classes of materials and were compared for cost effectiveness. This component performs the function of supporting the module along the edges and serves as the mechanical carrier between the module edge and the support frame. Manufacturers of suitable gaskets were surveyed and companies producing gaskets intended specifically for solar applications were identified.

(6) Sealants are compounds that fill the gap between the edge of the module and the surrounding gasket. They result in a seal that is impervious to liquid water and inhibits the transmission of air to the module edge. Suitable chemical classes and commercially available products were surveyed for use in this application.

(7) Differential thermal analysis: This technique was used to examine the thermal and thermal/oxidative stability of some of the candidate pottant compounds and compare their performance to the PVB and silicone polymers currently employed in solar module manufacture. Temperatures at the onset of degradation were determined in both air and nitrogen atmospheres to discriminate between oxidative and pyrolysis mechanisms.

(8) The evaluation of new primers for the module interfaces were continued. The primer formulations were based on a silane coupling agent that has been used with success in previous bonding work and were modified with the addition of a small amount of a peroxide to further promote reactivity. Bond strength determinations were run on glass, aluminum, mild steel and copper strips.

(9) The effect of the new primer on the corrosion sensitivity of metal surfaces was determined by encapsulating the primed metals in EVA pottant. The specimens were then evaluated in a heated salt spray chamber and the degrees of attack compared.

(10) A series of coatings was started in an outdoor test program to determine their effectiveness as soil resistant surface treatments. These compounds were based on acrylic, silicone and fluorosilane chemistries and were applied to low iron glass and two outer cover candidates, Tedlar and X22417 acrylic film (3M). The soil retention was determined by reduction in short circuit current as measured with a standard cell. Two months of data were recorded and the trends observed.

(11) Exposure of candidate encapsulation materials under RS/4 sunlamp radiation was continued. Specimens were withdrawn at periods of 60, 120 and 240 days for subsequent evaluation for physical properties and optical transmission. The performance of these materials serves as a guide for selection and refinement of formulations.

III. ETHYLENE/VINYL ACETATE POTANT (EVA)

Ethylene/vinyl acetate copolymer is an experimental material produced in sheet form and intended for use in the fabrication of solar modules. The copolymer was selected for its low cost, high transparency, and ease of processing. Additionally, it is hydrolysis resistant and may be chemically cured to a tough, rubbery encapsulant, providing mechanical protection to the cell.

This copolymer has been formulated for a rapid cure at high temperatures and also contains antioxidants and UV stabilizers to prolong its outdoor service life.

The full physical properties of this formulated resin are attained only after sufficient cure at elevated temperature. This crosslinking reaction (curing) is essential to develop the desired mechanical strength and to eliminate creep during thermal cycling. This material has been found to successfully pass the Jet Propulsion Laboratory thermal cycling test that ranges from -40°C to $+90^{\circ}\text{C}$.

The required time/temperature profile for the successful processing of this material appears in a subsequent discussion.

The ultimate properties obtained upon curing of this material are shown in the following table:

EVA FORMULA A9918

<u>Property (Cured)</u>	<u>Value</u>	<u>Units</u>
Ultimate tensile strength (ASTM D638)	1890	psi (133 Kg/cm ²)
Ultimate elongation (ASTM D638)	510	%
Tensile modulus (ASTM D638, 25 ^o C) (Young's or tangent modulus)	890	psi (63 Kg/cm ²)
Density	0.92	g/cc
Transmittance, % (total integrated transmittance from 350 nm to 800 nm) (ASTM E424, method A)	91	%
Hardness, Durometer	70	Shore A

Many methods of using this material for solar cell encapsulation are conceivable. One technique we have found to be particularly successful is that of vacuum bag lamination. In this process, bubble-free encapsulation

of the cells and cure of the resin is accomplished in the same step. This material is produced as a film of uniform thickness and is intended to be used in a lamination process. During lamination under heat and vacuum, the EVA compound softens (above 85°C) to a viscous fluid which facilitates flow around the solar cells, and fill of small mechanical cavities. Above 125°C , this EVA formulation subsequently cures to a tough, transparent, and thermally creep resistant rubber.

Springborn Laboratories, Inc. has had success in producing good quality modules with EVA through the use of a "double vacuum bag" laminator. The following sections describe the construction of this laminator, the cure properties of the EVA material, our lamination process, and a technique for measuring the degree of cure.

Vacuum Bag Laminator

A successful and predictable module fabrication process for EVA pottant has been achieved with a double vacuum bag technique. To implement this technique, a special piece of equipment was built. The apparatus, pictured in Figure 1, consists of a double sectioned aluminum picture frame enclosed on the top and bottom with aluminum plates. A flexible polymer diaphragm separates the upper and lower cavities. Each chamber has its own vacuum gauges and valves for the individual evacuation of each section. The top cover plate is permanently attached and sealed to the top cavity with bolts and silicone rubber gasket. The lower plate is removable and, in use, seals to the bottom of the lower frame piece with a silicone rubber "O" ring gasket. The diaphragm material employed to date is a high temperature nylon^(a) film of 0.003" thickness and is flexible, but not elastic in nature. Conceivably, many other types of films would work well in this application. Laminators have been constructed at Springborn Laboratories with the ability to fabricate modules up to 12 inches wide by 16 inches long (30cm x 40cm).

The lower cavity is used for the lamination process, requiring positioning of the module assembly below the flexible diaphragm. The top surface of the module assembly is made flush with the top edge of the lower cavity, by stacking a necessary number of thin metal plates in the bottom of the lower

a) "Capran" polyamide film, Allied Chemical Company.

cavity. The double vacuum bag design enables initial exposure of the module assembly to vacuum without simultaneous diaphragm compression. This enhances air exhaustion and eliminates cell breakage. To assure thorough air exhaustion, especially from large area modules, Springborn Laboratories, Inc. encourages the use of air release layers which are incorporated as an integral part of the module assembly. Springborn Laboratories, Inc. has had success with the use of 5-mil thick, non-woven glass cloths manufactured by Crane & Company, Inc.*; Dalton, Massachusetts. Experimentation has demonstrated that this 5-mil thick glass mat can be positioned above the active surface of the solar cells without optical penalty.

Diaphragm compression of the module assembly can be optionally implemented at any stage of the lamination cycle by pressurizing the upper cavity, but it is advised that compression be initiated or achieved before the temperature of the EVA reaches 120°C. At this temperature the EVA potant is at the lowest melt viscosity attainable before the cure reaction begins.

Module Assembly

In practice, the module components must be preassembled into a sandwich prior to the encapsulation step. The basic assembly of materials required for vacuum bag processing of both substrate and superstrate designed modules are illustrated with the following examples (from top to bottom, as fabricated):

Superstrate (a)		
White Plastic Film.		Back Cover
Clear EVA		Transparent Pottant
Craneglass		Air Release Mat
Solar Cells, With Interconnects (face down)		
Clear EVA		Transparent Pottant
Craneglass		Air Release Mat
Glass, Primed (b)		Superstrate

*Type 230; 5-mil thick, 0.8¢ per sq. ft.; marketed by Electrolock, Inc.; Chagrin Falls, Ohio (other grades and thicknesses are available from the same company).

(a) These reflect two basic designs which have been used with success at Springborn Laboratories, Inc. The clear EVA is used at a thickness of approximately 0.018 in. (0.45mm). The load bearing member, either substrate or superstrate, always faces the bottom of the assembly.

(b) A primer for EVA/Glass has been developed by Dow Corning, Corp., and experimental quantities are available from Springborn Laboratories, Inc. under the designation A-11861. Optionally, the user of the EVA material may prepare his own primer, the formulation of which is described in Table I.

Substrate (a)

Clear Plastic Film.	UV Screening Front Cover
Clear EVA	Transparent Pottant
Solar Cells, With Interconnects (face up)	
Crane glass	Air Release Mat
Clear EVA	Transparent Pottant
Substrate, Primed	Substrate

Once the basic module components for either design have been assembled, a 10-mil thick FEP^(b) release film cut to match the area size of the module is placed above and below the module assembly. The outer FEP film layers are then taped together over the edges of the module assembly with masking tape in order to contain the fluid EVA when it melts during the heating cycles. The wrap-around layer of masking tape is thus adhesively attached to the top and bottom FEP film layers, rather than to surfaces of the module. Although the module edges are taped firmly, entrapped air appears to diffuse out with no difficulty under evacuation. Masking tape has been used in this style of lamination operation, however it is conceivable that some type of innovation in equipment design may successfully eliminate this step.

The completed module assembly with taped edges is then placed in the lower cavity of the laminator, followed by evacuation at room temperature of both the upper and lower cavities.

EVA Cure Studies

The base EVA copolymer (Elvax 150, DuPont) is cured by the addition of an aliphatic peroxide curing agent. This curing agent thermally decomposes at elevated temperature to generate cure-active chemical species. The specific curing agent, Lupersol 101, was selected for the following reasons:

1. The ability to cure the copolymer efficiently to high gel contents.
2. Negligible decomposition at 85° to 90°C, the temperature range at which the EVA is extruded into film.
3. Chemically inert decomposition residues.
4. No ultraviolet (UV) sensitization with respect to the EVA.

(a) These reflect two basic designs which have been used with success at Springborn Laboratories, Inc. The clear EVA is used at a thickness of approximately 0.018 in. The load bearing member, either substrate or superstrate, always faces the bottom of the assembly.

(b) "Teflon" FEP film, E. I. DuPont de Nemours.

Laboratory experiments with this curing agent have established a time-temperature relationship for achieving acceptable and repeatable cure of the EVA. The cure curve is shown in Figure 2. This curve was established employing laboratory techniques wherein the EVA compound was brought almost instantaneously to temperature, followed by monitoring of the level of cure (gel content) as a function of cure time at constant temperature. The criterion of acceptable cure was achievement of mechanical creep resistance of the cured EVA at 90°C, which corresponded to gel contents in excess of 65%. It is to be noted that under these laboratory conditions, approximately 20 minutes are required at 150°C to achieve acceptable cure, and that the cure times increase by nearly a factor of three (3) for every 12°C decrease in cure temperature. A description of a technique of measure gel content is included in the Appendix, Table 1.

Due to the variation in processing requirements encountered in the industrial use of EVA, a series of tests were run to verify time/temperature cure conditions and examine the variations in cure efficiency. This was done under laboratory conditions using a heated platen press as the heat source. Twenty mil thick plaques of EVA A9918 were pressed at different times and temperatures and then subsequently analyzed for gel content to indicate the degree of cure. The following table records the results:

CURE PROFILE - EVA
Formulation Number A9918

<u>Cure Time</u>	<u>Degree of Cure (% Gel)</u>		
	<u>130°C</u>	<u>140°C</u>	<u>150°C</u>
1 minute			2.1
2 minutes		1.0	4.1
5 minutes		11.8	21.1
10 minutes	1.0	23.5	63.2
15 minutes	2.3	59.3	88.3
30 minutes	3.4	68.2	
60 minutes	32.1	80.6	

As may be seen, the 130°C temperature is ineffective in initiating cure. The 140°C temperature is effective, however it requires a thirty minute period of time to reach an acceptable gel content. This is in accordance with the results obtained by some module manufacturers, based on recent contacts. The highest temperature, 150°C, is the most suitable but still requires a full 15 minutes to develop a high degree of cure.

It is interesting to note that the times and temperatures resulting in acceptable polymer gel contents (over 70%) correlate well with the Half Life-Temperature Graph for the decomposition of Lupersol-101 in a benzene solution. The time/temperature requirements fall accurately (based on two points) on the curve of log peroxide half-life versus temperature. The curve is attached, Figure 2.

Laboratory experiments also indicate that the EVA copolymer cannot be acceptably cured below 120°C, even though the curing reaction (peroxide decomposition) is proceeding at a slow rate. The user of this experimental EVA material is cautioned that maintaining molten EVA for excessive lengths of time (in the temperature range between 85° and 120°) may result in depletion of the curing agent to a level where acceptable cure of the EVA cannot be achieved when the EVA is later heated to higher temperatures. This area of EVA cure technology has not been thoroughly studied.

The chemical species generated from the thermal decomposition of the peroxide are prevented from forming gas bubbles in the curing EVA by action of the lamination pressure. Laboratory experiments have adequately demonstrated that one (1) atmosphere of lamination pressure at 150°C will prevent gas bubble formation (i.e., bubble-free EVA). The use of lamination pressures at less than one atmosphere at 150°C may lead to insufficient containment pressure resulting in trapped gas bubbles in the cured EVA. For low pressure (<1 atmosphere) lamination, corrections may be made by trial-and-error lowering of the peak cure temperature, but this will also necessitate progressively longer cure times for the EVA.

A method for the quantitative analysis of peroxide and the other compounding ingredients in A9918 is being developed using high pressure liquid chromatography (HPLC). This method will be used to determine the critical

amount of peroxide required for cure at different points on the time/temperature curve; assess the amount of residual peroxide after cure; and be used for quality control analysis of the compounded/extruded product.

Lamination Process

The lamination process successfully employed at Springborn Laboratories, Inc. is described in the following:

The assembled module with taped edges is positioned in the lower cavity, and a microthermocouple is taped onto the FEP release film at the module center. The microthermocouple permits convenient monitoring of the module temperature during the lamination cycle. The flexible diaphragm and upper cavity is then positioned over the module and encloses it.

Both the upper and lower cavity are evacuated, and at least five minutes are allowed to elapse before heating in order to exhaust the air from within the module assembly. While under continuous vacuum in both the upper and lower cavity, the entire vacuum bag fixture is loaded between the preheated (150°C) platens of a hydraulic press which serves as the heat source. The ram pressure used is just sufficient to close the press and provide good heat transfer to the vacuum bag fixture. The pressure from the platen should rest on the frame of the fixture only and should not transmit any pressure to the surface of the module.

The time/temperature heating cycle of the module assembly after loading the vacuum bag fixture into the preheated (150°C) hydraulic press is shown in Figure 3. Experimentation with this heating process has demonstrated that a dwell time of 10 minutes at 150°C results in an acceptable EVA cure, which is less than the 20 minutes determined in the laboratory testing. The reduced dwell time is due to the degree of partial curing which occurs during the heat up time to 150°C (faster or slower heating rates may require adjustment of the dwell time at the peak cure temperature).

Samples of EVA taken from modules laminated by the process described and the associated time/temperature heating cycle exhibit acceptable cure and gel contents in excess of 75%.

In this process, pressurization of the upper cavity to one (1) atmosphere of pressure is started when the module assembly temperature reaches 120°C. The slow pressurization up to one atmosphere is accomplished by partial opening of the valve on the upper cavity chamber sufficiently to regulate the rate of pressure rise to require about 8 to 10 minutes for full atmospheric pressurization to be achieved. This pressurization scheme employed in our process is not to be inferred as either mandatory or optimum, and users of this experimental EVA material may explore alternative pressurization techniques. The double vacuum bag fixture also provides a capability to limit pressurization in the upper cavity to less than one atmosphere. Low pressure (< 1 atm.) lamination has not yet been experimentally investigated with respect to identifying the relationship between peak cure temperature and lamination pressure required to inhibit gas bubble formation from the peroxide decomposition.

Following the 10 minute dwell at 150°C, the assembly is removed from the press and permitted to cool. When a temperature of approximately 40°C is reached, the vacuum in the lower cavity may be released and the completed module removed from the vacuum fixture. A time/temperature profile and fabrication summary of this process is illustrated in Figure 3.

Modules prepared by the preceding process are fully cured, bubble-free and of good appearance. No evidence of cell or interconnect damage has been noticed.

The use of primer No. All861 results in excellent adhesion between the EVA pottant, glass, and many other surfaces (see formulation, Table 2).

It must be pointed out that the rate of temperature rise that the module assembly experiences during lamination may be an important factor. EVA heated up to the cure temperature too slowly may not cure properly due to depletion of the curing agent before the minimum EVA cure temperature of 120°C to 125°C is reached. The average EVA heating rate in our process is about 4°C per minute, however, faster heating rates are possible and may be found to be desirable. Failure of the EVA to achieve acceptable cure employing the time/temperature cure relationship given in Figure 2 may relate to slow EVA heating rates. The user should also be aware that our laboratory experience indicates that open exposure of this EVA material to air at the high cure temperatures may retard the cure due to oxygen inhibition.

Fabrication Process Summary

Our double vacuum bag lamination process may be summarized as a sequence of the following steps:

1. Assemble module construction materials, including the FEP release films (10 mil.), and seal the edges firmly with masking tape.
2. Place the preassembled module between the diaphragm picture frame and lower support plate.
3. Evacuate the entire assembly (both top and bottom chamber) through the side connections for at least 5 minutes, and with vacuum still applied.
4. Place the vacuum bag between the heated platen of a hydraulic press or any other heat source capable of making intimate contact. The temperature should be set to 150°C.
5. Follow as practically possible the time/temperature/pressure curve as shown in Figure 3.
 - (a) Heating rate should be in the order of 4°C/min.
 - (b) The top cavity should be slowly returned to ambient pressure starting when the module temperature reaches approximately 120°C. Our practice is to regulate the rate of pressure increase such that 8 to 10 minutes are required to achieve atmospheric pressure in the upper cavity. Heating to 150°C is continued without interruption during this step.
 - (c) Allow to cure at a temperature of 150°C for a period of at least 10 minutes.
6. Cool to room temperature, release vacuum, remove the module assembly, peel off the masking tape, and lift away the FEP films. The edges of the fabricated module can be cleaned up, if necessary, with a sharp blade.

It must be pointed out that variations in the time/temperature requirements to fully cure the pottant may vary with different equipment and module assemblies. The time and temperature cure relationship is not a simple function. Ultimate temperature reached, heat transfer rates, and inhibition by air all may cause the rate and degree of cure to vary from process to process. The procedure previously described has been employed at Springborn Laboratories for the production of many experimental modules and has resulted in good quality modules of reproducible cure and appearance.

The advantages with this encapsulation method are briefly summarized as follows:

- (a) Rapid fabrication, approximately, 1-hour cycle
- (b) Bubble and void free
- (c) Ease of materials handling
- (d) Good cure of the resin
- (e) Good adhesion (with the primers used to date)
- (f) No cell shifting
- (g) Minimal loss of encapsulant during fusion
- (h) No cell or interconnect damage
- (i) Good potential for automation

Aging Studies

Specimens of cured EVA encapsulant have been under continual exposure to elevated aging conditions in order to determine the durability of the material compared to the degradation rates of comparable polymeric materials. Specimens of EVA-9918 have just been retrieved from long term oven aging at 70 , 90 and 130°C. The exposure periods have been 1 week, 3 weeks, 2 months and 10 months (7,200 hours). The specimens surviving the 10 month exposure at 90°C do not appear to be adversely affected and no appreciable decay of optical or mechanical properties has been found. The results of the thermal aging are shown on Table 3. Cured EVA specimens have also been under exposure to RS/4 sunlamp radiation at a temperature of 50°C. This exposure is useful for the ranking of polymers in terms of their ultraviolet stability. Although it is material, additive and process dependant information concerning the UV stability and relative performance of the pottant may be obtained. As a point of reference unstabilized polyethylene will last about 400 hours before the tensile strength has decreased by 50%. Polypropylene shows serious signs of degradation within about 200 hours. The EVA specimens with no additional external coating have survived 22,700 hours to date with no observable decay in optical or mechanical properties. In a relative sense this implies excellent UV stability of this compound. Unstabilized and uncured EVA shows noticable signs of degradation after 500 hours exposure. It appears that the fully formulated compound is performing very well. In addition, the EVA pottant will receive extra protection in the module due to its position behind glass (superstrate construction) or a durable outer cover (substrate construction).

Pottants are the rubbery transparent materials which serve as the encapsulation medium directly in contact with the solar cell. The required properties of the pottant are transparency, thermal stability, UV resistance, low modulus for stress relief, the ability to be crosslinked (for thermal creep resistance), and others. In addition to these performance properties the pottant must be usable in some fabrication scheme for the preparation of solar modules without damage to the cells, interconnects or other components. Investigations by Springborn Laboratories into materials suitable for pottants also necessitated the examination of possible processing and fabrication techniques. Two methods evolved from these studies, lamination and casting. Lamination involves the preparation of a sandwich composed of the pottant and other components in sheet form which are then fused under heat and vacuum to give the completed module. Casting involves the use of a liquid pottant which is pumped into a cavity containing the other components. After filling (and heating in some cases) the pottant sets to a solid compound and develops its final cured properties.

Investigations of pottants as alternates to EVA have been under investigation. These compounds represent "second choice" materials in the event that the EVA pottant appears to be unsuitable for a particular module design or process. These investigations, hopefully, will also result in a few alternate choices of pottant for solar module manufacturers who may be pursuing different fabrication concepts than those emphasized in this report.

In addition to the reevaluation of the cure behavior of the EVA lamination pottant presented in the previous section, this year's work has pursued the preparation of industrial evaluation grades of one other lamination compound, ethylene/methyl acrylate, and two syrup casting compounds, butyl acrylate and aliphatic urethane.

A. Ethylene/Methyl Acrylate

The development work of the past year has emphasized EVA (ethylene vinyl acetate) as the pottant due to its desirable properties and its potential for commercial readiness. Another modified polymer is currently available in roll form from Springborn Laboratories for industrial evaluation.

This new pottant is based on ethylene/methyl acrylate, a random copolymer of ethylene gas and methyl acrylate acrylic monomer. This is a versatile polymer with wide processing latitude, good thermal stability, it is less crystalline and also softer than polyethylene. Although it has been commercially available in good supply for years, ethylene/methyl acrylate (referred to as EMA) is probably the least known of all of the ethylene copolymers. EMA is produced in a conventional high pressure reactor in which the methyl acrylate monomer is injected into an ethylene stream in the reactor. Under proper control of pressure, temperature and catalysts, the two polymerize to produce the copolymer. During the polymerization, the methyl acrylate enters the polyethylene backbone to produce side branches that subsequently interfere with the crystallization of the ethylene portions and result in the alteration of many properties. These acrylate groups occur at random positions along the backbone of the polymer and in most commercial resins constitute about 20% of the polymer weight.

The most noticable changes induced by the presence of the acrylate group are lowering of the melting point (Vicat softening point), reduction in stiffness (modulus), an improvement in stress crack resistance, an increase in the dielectric strength, a decrease in the softness and an increase in the total optical transmission. These properties result in a resin that has potential for use as a solar module encapsulant.^(a) A property comparison between EMA and low density polyethylene is shown in the following table:

(a) Willis, P. and Baum, B., Investigation of the Test Methods, Material Properties and Processes for Solar Cell Encapsulants, Seventeenth Quarterly Report to Jet Propulsion Laboratories, Contract #954527, Springborn Laboratories, Enfield, Connecticut, September 1980.

(a)

Property	Ethylene-methyl acrylate copolymer	Low-density polyethylene homopolymer
Melt index	2.4	2
Density, grams per cubic centimeter	0.942	0.917
Comonomer content, percent	20	0
Vicat softening point, °F	138	194
Tensile strength, psi	1620	1850
Elongation, percent	720	650
Hardness, Shore D	35	46
Flexural stiffness psi	4000	18,500
Stress-cracking resistance (hotsoyol at 50°C)	no failure in two weeks	90 % failures in 1 day
Dielectric constant at 100 kilohertz	3.1	2.3
Dissipation factor at 100 kilohertz	0.015	0.0002
Low-temperature brittleness	no failures to -76°C	10 % failures to -76°C

(a.) Reprinted from "Plastics Technology", February, 1980.

EMA also has the valuable properties of low melt temperature when used with conventional processing equipment, good melt adhesion to a wide variety of substrates, good heat sealability and unexpectedly high thermal stability when compared to other olefin based polymers. EMA pellets are not hydrophilic as are some of the other copolymers and consequently it can be stored and handled in normal containers and resin silos without the fear of water absorption.

The only source of transparent thermoplastic EMA polymers in the United States is Gulf Oil Chemicals Company, Orange, Texas, who produce the base resin at costs in the order of \$0.59/pound. Applications for this polymer include high strength films for food and packaging applications, disposable "rubber" gloves, and co-extruded films with other resins for heat seal applications. Gulf Oil Chemicals Company produce three commercial grades of EMA that vary in melt index and additives. The three grades compare as follows:

	<u>EMA Grade Number</u>		
	<u>2205</u>	<u>2255*</u>	<u>TD-938</u>
Melt Index (ASTM D-1238-E)	2.0	2.4	6.0
Optical Transmission Method ASTM 424-A	89.6%	89.8%	88.1%
Comonomer Content	20%	17%	20%
Refractive Index, n_D	1.49	1.49	1.49

*Contains anti-block agent, lubricant.

Other commercial sources of EMA resins were also surveyed due to the promising characteristics of this material. Two others were identified; Northern Petrochemical Company, Omaha, Nebraska and E. I. DuPont de Nemours, Wilmington, Delaware. Northern Petrochemical's resin is referred to as "Specialty Resin 1230" and has a melt index of 12 gms/10 min. and a Shore A hardness value of 40. This resin will not be explored under the JPL program due to the fact that it is currently a "foreign source" material, being prepared by BASF Corporation, Baden, Germany and only distributed in the United States. The other EMA resin available from DuPont has the tradename "Vamac N-123" and is an opaque masterbatchethylene/acrylic elastomer containing fumed silica, stabilizers and processings aids. It is not suitable for use as a pottant due to its negligible light transmission.

Experiments were conducted to determine if curable lamination compounds could be prepared from EMA resins. The Gulf product 2205 was used as a starting point and cure trials were run with high temperature aliphatic peroxides at a level of 1.5% by weight. The peroxide was blended into the resin on a heated (100°C) two roll mill for a period of five minutes. The formulation was then removed and plaques were compression molded at 150°C for 20 minutes. Gel was subsequently determined by extraction with hot toluene. The following results were obtained:

<u>Aliphatic Peroxide</u>	<u>Temperature of Half-Life</u>	<u>Polymer Gel Content</u>
Lupersol 101	138°C	63.4%
Lupersol 231	112°C	79.5%
Lupersol 130	149°C	0
Vulcup-R ^(a)	137°C	72.0%

(a) Vulcup-R is not an aliphatic peroxide and is included for comparison of cure efficiencies only.

Lupersol 231 was initially selected as the peroxide for use in complete formulations (incorporating antioxidants and ultraviolet stabilizers) but was later abandoned due to its thermal sensitivity. Due to the demonstrated efficiency of the formulation, the same stabilizer compounds used in the EVA formulation were also used in the trial EMA formulations, as follows:

<u>Ingredient</u>	<u>Quantity</u>
EMA, base resin	100 parts
Peroxide	1.5 parts
Cyasorb UV-531	0.3 parts
Tinuvin 770	0.1 parts
Naugard-P	0.2 parts

This formulation was tested with each of the three Gulf EMA polymers and cure trials resulted in consistently high gel values of 76-68%.

A fully compounded version of EMA (formulation A11877) was then run through the Brabender laboratory extruder to determine the processing conditions required to produce an extruded sheet suitable for the lamination approach to module fabrication. As with the EVA counterpart, the resin pellets (type 2205) were tumble blended with the peroxide and stabilizing additives and run directly into the hopper of the extruder. The resulting sheet material was of good quality, more easily controllable than EVA and could be extruded in thinner gauges. Extrusion proceeded smoothly at a barrel temperature of 110°C. The throughput was steady and approximately the same speed as the EVA, with a barrel residence time of approximately 3-4 minutes.

Sheet resulting from this extrusion procedure was cured and analyzed for gel content. A low gel content of only 40% resulted. This was thought to be due to the higher melt viscosity of the EMA resin and insufficient blending of the peroxide during the extrusion process. This problem was expected to disappear with the use of the large (2 1/2") extruder and higher melt index resin.

The higher melt index resin (TD 938) was ordered from Gulf Oil Chemicals, Inc. in sufficient quantity to reevaluate the formulation on a laboratory scale and also for the large trial run. This new material (melt index 6 as opposed to 2) was compounded in the same manner as the previous copolymer and extruded without difficulty. Gel contents obtained with this formulation were found to be in the range of 74-78%. The blending properties of this polymer appear to be superior and subsequent formulations used it as the EMA base resin.

A brief experiment was also tried to determine if an alloy of EMA and EVA could be prepared that would have a melt index in a range more suitable for the compounding operation. A blend of EMA (TD-938) and EVA (Elvax-150) was prepared on a differential two roll rubber mill. The composition was adjusted for a melt index of 15 by using a composition of 74% EMA and 26% EVA. The two resins appear to be melt incompatible and result in an opaque polymer mass with poor transmission in molded sheets. This approach was discontinued.

The EMA base resin was therefore changed to the material designated TD-938 with the higher melt flow value. This change was to facilitate more thorough compounding and possibly improve module fabrication due to the lower melt viscosity. The peroxide was also reevaluated in this formula and Lupersol-101 was found to be marginally more effective in raising the cured gel contents than the Lupersol 231. Its use is also advantageous because it has a higher thermal stability and will more easily tolerate shear/mixing in the extrusion process without premature decomposition. The new formulation (Springborn number A13439) was cured for 30 minutes at 150°C and resulted in a gel content of 64%.

A quantity of the revised compound using the more stable and more effective Lupersol-101 was prepared by dry blending. This formulation was used for the preparation of the first pilot plant run to provide small quantities for industrial evaluation. Table 4 of the Appendix summarizes the formulation, equipment and process parameters used in this extrusion operation.

The extrusion process proceeded smoothly without any special precautions, however attention was given to the extruder temperature profile to make sure that temperatures in excess of 110°C were not attained due to heat of shear from the internal mixing operation. A two stage screw was used to facilitate the compounding of the additives into the polymer. The extruded sheet was uniform in gauge (18-20 mils), hazy and translucent in appearance and was wound onto a 3" diameter cardboard core for shipment and convenience in use.

No release paper interleaf was used to separate the plies of this product. The resin has very low surface tack and may be wound and unwound easily without blocking difficulties.

Cure profiles were determined in the laboratory by curing compression molded plaques in a heated platen press for varying lengths of time and then measuring the gel content. The following table gives the results:

CURE PROFILE - EMA

Formulation Number A-13439

<u>Cure Time</u>	<u>Degree of Cure, % Gel</u>		
	<u>130°C</u>	<u>140°C</u>	<u>150°C</u>
10 minutes			0%
20 minutes			37%
30 minutes		Low Gel	53%
40 minutes	Low Gel	34%	63%
60 minutes	Low Gel	47%	65%

These results may be used as a general guide for the determination of the correct cure time required during module fabrication.

Unlike the EVA resin pottant produced by Springborn (Formula A9918), the EMA resin is not as dependent on cure to develop its full physical properties. Curing results in a slight increase in tensile properties and a slight improvement in optical transmission. Properties (except where noted) were measured at a gel content of 40% and are given as follows:

EMA 13439

Cured Properties

<u>Property</u>	<u>Value</u>	<u>Units</u>	
Ultimate tensile strength (ASTM D-638)	2,080	psi	(146 Kg/cm ²)
Ultimate elongation (ASTM D-638)	570	%	
Tangent modulus (Young's) (ASTM D-638)	3,240	psi	(228 Kg/cm ²)
Total integrated transmission (ASTM E-424-A)	90.5	%	
Melt Index-uncured resin (ASTM D-1238-E)	6.0	gm/10 min	
Comonomer content (methyl acrylate)	20	% weight	
Refractive Index, n_D	1.49		
Softening point, Vicat (Uncured resin)	55	°C	
Low temperature brittleness	76	°C	
Hardness, Shore D	35		

The degree of cure in the EMA based pottant is not as important as it is in the EVA pottant. The reason for curing pottant materials is to prevent destructive creep or flow that may occur in the module at elevated operating temperatures. EVA will creep very badly and flow off the module surface if it is not cured (vulcanized) and subsequently exposed to the upper limit use temperature (90°C). The requirement is not as stringent for the EMA based pottant, however. Two modules were prepared with both EMA 2205 and EMA TD-938 base resins without any cure additives at all. These modules were then placed in an air oven set for 90°C for a period of one month. At the end of this period of time no creep of the pottant could be noticed and both modules were in the same condition as when they had been

fabricated. Larger sized modules with uncured resin are currently undergoing the JPL thermal/humidity cycling test to verify the apparent lack of thermal creep. The necessity for curing the EMA and the required gel content (if any) is also being determined by additional experiments at Springborn Laboratories.

The EMA 13439 pottant requires the use of a primer for effective and reliable bonding to the other components such as cells, interconnects and the glass superstrate. Preliminary experiments have found that the primer recommended by Springborn (number A11861) for the EVA pottant system is also highly effective with this new pottant. Tenacious bonds to glass result with the use of this primer that appear to be resistant to boiling water and result in shattering of the glass when tested for peel strength.

Samples of the extruded EMA were compression molded into plaques and then cured between Teflon-FEP films to yield optically flat surfaces. Total integrated transmission values were then determined (ASTM E-424-A) over the range of 350 nm to 800 nm. The total transmission was found to be 90.5%.

Research quantities of EMA pottant are now available from Springborn Laboratories in extruded sheet form suitable for lamination experiments. Larger quantities will be available at a later date depending on the response from industry or will be prepared on a custom order basis.

B. Butyl Acrylate

The polybutyl acrylate pottant was originally investigated at JPL and found to be a desirable material for use as a pottant for reasons of its physical properties and its photostability. A study of the photochemistry indicates that poly n-butyl acrylate (cured) forms a stable crosslinked network that undergoes chain scission and crosslinking at equal rates when exposed to ultraviolet radiation in the photoactive regions of the spectrum.^(a) A study of the wavelength dependance of the photodegradation of the polyacrylates shows that photoreactivity continues up to 310 nm, only barely into the solar spectrum. This indicates that the acrylic elastomer will require less stabilization than materials with strong absorptions that reach far into the terrestrial ultraviolet.^(b)

The compound originally prepared by JPL was composed of a premade butyl acrylate polymer that was then dissolved in a quantity of monomer to yield a pourable syrup. This syrup was then cured by heating in the presence of a free radical initiator. The cured material produced by this method is a water-white highly transparent elastomer of low modulus.

Large quantities of butyl acrylate (monomer/polymer) syrup were prepared for cure tests and large scale evaluation. This material was initially prepared in the manner suggested by JPL, a laboratory procedure which is given in the appendix, Table 5.

The syrup prepared by this method was stored under refrigeration and protected from sunlight to prevent the premature cure of the system.

Initial studies of the required cure conditions were also conducted at JPL using AIBN (azobis-isobutyronitrile) at a level of 0.01 weight percent as the free radical initiator and curing agent. Periods of four to sixteen hours at 80°C resulted in cured polymer with gel contents of 61% to 68% (by extraction) and over 90% conversion of the monomer to polymer. It was found that with this initiator, appreciable gel contents only occurred at temperatures in the range of 80°C - 90°C, and that temperatures above or below this range gave only small quantities of gel.

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- (a) Gupta, A., Photodegradation of Polymeric Encapsulants of Solar Cell Modules, LSA document 5101-77, 8/10/78, Jet Propulsion Laboratory Pasadena, California.
- (b) Morimoto, K., and Suzuki, S., Journal of Applied Polymer Science, 16, 2947, (1972).

Cure experiments were continued at Springborn Laboratories with the use of different initiators, higher levels and different temperatures. One hour was used as the standard cure time in all cases in order to give a closer approximation to possible module fabrication speeds. Table 6 in the appendix gives the results of these experiments.

As can be seen from the table, very low gel contents (crosslinked polymer) resulted in all cases. Although most of the initiators tried were effective in terms of initiating polymerization only benzoyl peroxide was effective in causing much of any gel content to appear at all. This is most likely due to the high hydrogen abstraction ability of the benzoyloxy free radical. All the experiments, except for those employing Lupersol 101, gave complete polymerization of the syrup.

Initial attempts to prepare experimental modules with this compound were not immediately successful due to lack of technique in terms of handling this material. A jig is required that serves to hold the front and back cover in place so that the fluid may be pumped in without leakage and loss. The jig must also be capable of holding the assembly throughout the heating and curing cycle. First attempts failed due to loss of pottant due to poor edge sealing. Masonite/Tedlar (substrate design) modules bonded with adhesives leaked due to attack on the adhesive. Other designs incorporated silicone rubber gaskets clamped between the rigid Masonite substrate on one side and the Tedlar cover film supported by a sheet of aluminum on the other. Two holes were left in the gasketing to permit the filling and overflow of pottant. The clamped assembly, after filling, was then transferred to an air oven set for 80°C. The cure process was completed after 3-5 hours and the modules were removed and permitted to cool. The pottant was found to have cured to a crystal clear rubbery compound and was completely bubble free, however the Tedlar film was somewhat wrinkled on the back due to shrinkage of the resin during the cure process.

The basic syrup formulation with AIBN initiator was shipped to Solar Power Corporation for industrial evaluation. Two modules were prepared, one in a pressurized autoclave and the other by the normal air oven technique. Both modules were easily handled by the standard industrial technique used for the fabrication of cast pottants and could be used as a direct replacement for the RTV silicone rubber fluids with no difficulty. Cure was accomplished

in an 80°C air oven for two hours. Both modules were filled with hundreds of bubbles, presumably due to the use of the AIBN initiator. This compound produces one mole of nitrogen gas per mole at the decomposition temperature and is widely used commercially as a "blowing agent" in the fabrication of plastic foams.

Experiments to reformulate the butyl acrylate syrup system were conducted with the goals of reducing the cure temperature, reducing the cure time, and eliminating the formation of bubbles in the cured material. The first attempt to accomplish this was the copolymerization of the butyl acrylate with a difunctional compound to incorporate crosslinkable groups into the backbone of the polymer that could be cured under milder conditions and without the use of AIBN.

A trial polymerization was carried out as previously described with the exception that 3% of the butyl acrylate monomer was replaced by 5-ethylidene-2-norbornene (ENB). This compound is used commercially as the crosslinking agent in certain EPDM rubbers to render them curable. The intention was to produce a butyl acrylate polymer with pendant vinyl functional groups. The resulting polymer solution was worked up as usual with the removal of the solvent and subsequent dissolving in more BA monomer. The devolatilized polymer dissolved with extreme difficulty and gave a thick gel-like solution indicating the possibility of some premature crosslinking resulting in molecular weight increase. Two runs were tried and tested for gel content by curing with AIBN at 60°C. The average gel content was found to be only 33%, not too much beyond that achieved through the hydrogen abstraction mechanism resulting from a peroxide initiator.

A second approach was investigated, employing the addition of individual difunctional acrylic monomers to the completed syrup formulation. Candidate monomers were selected and incorporated into the syrup at a level of 5% by weight. Curing was attempted at 60°C for one hour using 0.5% of AIBN as the cure initiator. The cured gel content was determined by weight loss resulting from solvent extraction, as usual. Table 7 of the appendix gives the results of crosslinking agent selection in the butyl acrylate system.

Most of the formulations that gelled had similar swell index values indicating similar numbers of crosslinks (crosslink density). The acrylate functional agents appeared to give higher gel contents than the methacrylates and SR-238 gave a noticable higher value (68%) than the other compounds screened. Subsequent experiments were conducted with formulations based on this crosslinking agent only. The modified base syrup has the formulation: polybutyl acrylate resin, 35%; butyl acrylate monomer, 60%; SR-238 (hexanediol diacrylate), 5%. The new composition was found to have viscosity of approximately 10,000 centipoise at room temperature.

Cure tests with different initiators and temperatures were run with this syrup to determine the efficiency and range of cure conditions. Samples were cured under nitrogen with 0.5% of selected initiators at various temperatures, tabulated as follows:

CURE EXPERIMENTS

Modified Butyl Acrylate Syrup, Al2805
(5% 1,6-Hexanediol Diacrylate)

Initiator	Temperature	Time	Swell Index	Gel
Lupersol 225 (di-(sec-butyl) ^(a) Peroxy-dicarbonate)	25°C	6 hrs	NP	NP
	50°C	1 hr	NP	NP
	50°C	16 hrs	NP	NP
Lupersol-11 ^(a) (t-butyl peroxy pivalate)	25°C	6 hrs	NP	0
	50°C	1 hr	360%	87%
BPO (benzoyl peroxide)	60°C	1 hr	470%	80%
Lupersol ANC ^(a) (benzoyl peroxide dispersed in 45% DOP plasticizer)	60°C	1 hr	400%	80%
AIBN (azobisisobutyronitrile)	60°C	1 hr	-	68%

(NP) = No polymerization

(a) Products of Lucidol Division, Pennwalt Corp., Buffalo, New York

The best initial results were obtained with Lupersol-11, an aliphatic peroxide and benzoyl peroxide. The Luperco ANS plasticized benzoyl peroxide was evaluated because these formulations must be shipped out for industrial evaluation. Plain 100% benzoyl peroxide presents a fire hazard and is consequently dangerous to send by common carrier.

Plaques of cured material were prepared to determine physical properties and their dependance on the cure system. The following table shows the results of stress/strain analysis (ASTM D-638):

POLYBUTYL ACRYLATE POTTANT

(A12805)

Physical Properties of Cured Material

Initiator	AIBN	Benzoyl ^(a) Peroxide	Benzoyl ^(a) Peroxide	Lupersol-11
Level, %	0.5	0.5	0.1	0.5
Time, Hrs.	1	1	3	3
Temperature, C	60	60	60	50
Hardness (Shore A)	43	43	44	44
Tensile Strength, psi	267	138	181	202
Modulus (100% Elong)	288	-	291	284
Ultimate Elongation	100%	50%	100%	100%
% Gel	85	84	83	84

(a) Luperco ANS, 55% BPO

The use of difunctional acrylic crosslinking agents appears to be a successful modification to the butyl acrylate pottant system. High gel contents have been obtained at reasonably low temperatures and much shorter cure times than required in the original formulation. AIBN, benzoyl peroxide and aliphatic peroxides are all found to be effective for producing the gel contents necessary for resistance to thermal creep.

AIBN or other azo compounds are more desirable than benzoyl peroxide due to the fact that they are not oxidizing agents that could result in a certain degree of decomposition of the polymer. Also most grades are not

aromatic in composition. It is desirable to avoid aromatic compounds if possible due to the fact that the aryl ring is a UV absorber that could possibly decrease the weathering resistance of the final cured compound.

Further experiments were conducted on cure systems for the polybutyl acrylate pottant system with the hope of finding a room temperature cure chemistry that would remove the need for oven heating after module fabrication. The experiments involved polymerization of the syrup at lower temperatures, the screening of lower temperature catalysts and the use of "promoters" that cause the cure reaction to proceed at a faster rate. A number of systems were found to give a wide range of time/temperature conditions resulting in good cure of the syrup. The results of these experiments are summarized in Table 8 in the appendix.

As may be seen from an examination of the table, a wide variety of pot lives, cure temperatures and cure times are available for use with this resin system. The best overall properties were obtained with the use of Lupersol-11, both promoted and unpromoted. Mixed syrup/catalyst formulations do not appear to cure under room temperature conditions, therefore may be used for fabrication during an eight hour shift; however they can be cured fairly rapidly at low (35°C) temperatures after the module has been filled with the syrup. The use of a promoter, stannous octoate, permits the cure to take place as low as 35°C and, at higher temperatures, cuts the cure time by approximately 1/2 when compared to the unpromoted system. The other initiators investigated, Lupersol-225, Benzoyl peroxide and Vazo - 33W, are either ineffective, cure too slowly or cure too rapidly with a short room temperature pot life. Lupersol-11 was the best selection between these extremes. It also results in slightly improved physical properties over the others, as is seen in the following table:

POLYBUTYL ACRYLATE POTTANT
Cured Properties vs. Initiator System

Initiator	Level	Cure Time ^(a)	Cure ^(b) Temperature	Strength	Elongation
	(%)	(min)	°C	(psi)	(%)
Benzoyl Peroxide	0.5	60	60	138	50
Benzoyl Peroxide	0.1	180	60	181	100
AIBN	0.5	60	60	267	100
Lupersol-11	0.5	180	50	202	100
Vazo 33W	0.5	60	25	138	74
Vazo 33W	0.1	60	25	91	55
Vazo 33W	0.5	60	25	99	63
Stannous Octoate	0.1				

(a) Minimum time permitted, cure may have taken place in much shorter time.

(b) Temperature at which polymerization initiated, does not include exotherm.

In general, it has been found that the butyl acrylate syrup pottant is a useful and rapid curing casting syrup that may be initiated using a wide variety of initiators and time/temperature requirements. There is some dependence of physical properties on the type of initiator used. The higher temperature cure systems appear to result in slightly higher elongations and noticeably better tensile strengths.

Despite the apparent success with this formulation, the study of initiators had to be extended. Lupersol-11 (Lucidol Corporation, Buffalo, New York) requires refrigerated shipment and is classified as a "deflagration hazard". This material has a self-accelerating decomposition temperature (SADT) of 85°F (30°C) at which point it undergoes sudden decomposition with the generation of force and/or smoke and fire. Although appropriate for laboratory use, this material may be too dangerous for general industrial application. An alternative was consequently sought.

Aliphatic peroxides were selected from lower hazard categories and screened for efficiency in curing the butyl acrylate syrup pottant, both with and without the presence of the promoter (stannous octoate). The following table records the data obtained on cure times at 60°C with a variety of these safer compounds:

Low Hazard Peroxide Initiators For
Butyl Acrylate Pottant

<u>Initiator</u>	<u>Time to Cure (minutes) at 60°C</u>	
	<u>Butyl Acrylate w/ 0.5% Initiator</u>	<u>Butyl Acrylate w/ 0.5% Initiator and 0.1% Promoter (c)</u>
Alperox-F ^(a)	18	9
Lupersol 220-D50	NP	NP
Lupersol 256 ^(b)	13	28
Lupersol 101	NP	NP
Lupersol 130	NP	NP
Lupersol 231	NP	NP

(a) Alperox-F is Lauroyl peroxide, Lucidol Corporation, Buffalo, NY

(b) Lupersol 256 Dimethyl -2,5- bis (2-ethyl hexanoyl-peroxy) hexane

(c) Promoter, M&T catalyst Number T-9

Of the two peroxides that function well as initiators, the first, Alperox-F (lauroyl peroxide) was selected for further use due to its lower hazard rating. This compound falls into the lowest hazard rating of flammable peroxide compounds; "low fire or negligible hazard". It has a self-accelerating decomposition temperature (SADT) of 120°F (50°C) at which point it undergoes slow decomposition accompanied by mild gassing or bubbling. This compound is thermally stable, has no shock sensitivity, decomposes mildly at high temperatures and constitutes a negligible fire hazard. Flammability tests done at Springborn Laboratories with a 5-pound quantity found the material difficult to ignite and maintain burning.

Experiments were performed to assess the efficiency and time/temperature requirements with Alperox-F. The time to cure was determined at room temperature, and two potentially useful fabrication temperatures, 50°C and 60°C. The experiments were run with both promoted and unpromoted butyl acrylate syrup with the following results:

Butyl Acrylate Syrup Number Al2805 with:	<u>Time to Cure, Minutes</u>		
	<u>Room Temperature</u>	<u>50°C</u>	<u>60°C</u>
Alperox-F, 0.5%	NP	NP	18
Alperox-F, 0.5% Promoter T-9, 0.1%	NP	25	9

As may be seen, the cure reaction may be conveniently initiated at temperatures as low as 50°C with a promoted system yet the mixed syrup does not appear to advance at room temperature. Specimens of mixed syrups were tested for cure after 18 hours at 25°C and were found to cure satisfactorily within approximately 50 minutes at 60°C. The reason for the increased time required cannot be explained at this time.

The last step in the formulation of this syrup to get a product ready for evaluation purposes involved the incorporation of additives to impart further UV/weathering stability to this resin. A survey of the literature resulted in a combination of stabilizers that have been found to be effective in acrylic resins. This combination of stabilizers was subsequently examined for cure compatability and an additional compound, 5-vinyl tinuvin was included as an absorber capable of coreaction during the cure. The results of these formulations appear in Table 9 in the appendix.

The best overall formulation based on clarity, cure requirements efficiency of cure and physical properties was selected from this table and constitutes the first industrially ready compound that will be sampled to industry for evaluation purposes. This material will be produced at Springborn Laboratories, Inc. in research quantities under the designation Butyl acrylate, 13870, and will have the following composition:

Formulation Number: BA-13870

<u>Ingredient</u>	<u>%</u>	<u>Parts</u>	
Butyl Acrylate, Polymer	34.72	35	100 parts
Butyl Acrylate, Monomer	59.52	60	"resin"
1,6-Hexanediol Diacrylate ^(a)	4.96	5	
Tinuvin-P ^(b)	0.248	0.25	
Tinuvin 770 ^(c)	0.0496	0.05	

Alperox-F ^(d) (initiator)	0.496	0.50	
	<u>99.99%</u>	<u>100.80</u>	

(a) "SR-238", Sartomer Corporation, Essington, PA.

(b) 2(2'-Hydroxy-5-methyl phenyl)benzotriazole, Ciba-Geigy, Ardsley, NY.

(c) Bis(2,2',6,6'-tetramethyl-piperidinyl-4)sebacate, Ciba Geigy, Ardsley, NY.

(d) Lauroyl peroxide, Lucidol Division of Pennwalt Corporation, Buffalo, NY.

In use, the formulation is completely compounded with the ingredients shown, except for the initiator (Alperox-F) which is blended into the syrup immediately before use. After mixing the initiator (a white powder) in with the syrup, the mixture is then degassed with stirring under vacuum at room temperature to remove air bubbles that may inhibit the cure and result in voids in the pottant. Alternatively, the initiator may be combined with the base syrup in an airless mixing process. The solid initiator does, however, take a period of time to dissolve (5-10 minutes at room temperature). Initiator that has been predispersed in a small quantity of inert plasticizer seems to blend in much faster and eliminates the time required for solution to occur.

As is shown in entry number 11 on Table 9 in the appendix, completely formulated compositions of this syrup are stable for at least one day without premature cure occurring and at 50°C the cure time is still in excess of one hour. This characteristic provides for ample pot life and permits the preparation of syrup for an entire day's run to be done ahead of time. Cure is accomplished easily at temperatures of 60-70°C. The cure time at 60°C has been found to be in the order of nineteen minutes, and at 70°C, about 14 minutes. Higher temperatures would result in further reductions in time.

After cure, the material is a transparent low modulus rubber with the following measured properties:

<u>BA 13870</u>	<u>Value</u>	<u>Units</u>
Total Integrated Transmission, %T (350-800 nm)	89	%
Refractive Index, n_D	1.47	-
Gel Content Extraction	80	%
Volatiles, Residual	0.7	%
Tensile Strength ^(a)	293	psi
Ultimate Elongation ^(a)	110	%
Modulus, Young's or Tangent	90	psi

(a) ASTM S-638, at 25°C

This pottant has a very high heat of polymerization and generates considerable exotherm when the cure process starts. This accounts also for the rapid rate of conversion. The cure reaction is essentially complete within about 5 minutes after initiation.

A simple calorimeter was used to measure the heat of polymerization developed during the cure reaction. The total heat of reaction was found to be in the order of 77 gram-calories per gram of syrup.^(a) This is equivalent to approximately 138 BTU/pound and is developed within a ten or fifteen minute period as the cure proceeds. During the cure cycle in fabrication, it would be advantageous to have the modules in such a location that the excess energy from this exotherm may be dissipated (circulating air oven).

Additionally, the fast rate causes thermal stresses in the curing resin and, combined with polymerization shrinkage, may result in the appearance of fractures. These effects do not appear to be troublesome in thin sections (100 mils) however, where the exotherm is dissipated. Plaques produced in standard molds cure with no difficulty to clear rubbery sheets with slight surface tack.

(a) This calculates to approximately -63 KJ mole^{-1} heat of polymerization for pure butyl acrylate. Literature values are: styrene, -69 KJ mole^{-1} , and methyl methacrylate, -58 KJ mole^{-1} .

A minimodule of 11" x 19" dimensions was prepared, containing 36 fully interconnected half round cells. The module was of the glass superstrate design and after filling with the experimental syrup, was cured in a circulating air oven at 60°C for a little over one hour. The resulting module showed no signs of damaged cells, was fully cured, and with the exception of two small areas that contained pumped in air, was of good quality and appearance. No evidence of gassing resulting from decomposition of the initiator system was noticed. The module is currently undergoing thermal/humidity cycle testing according to JPL specifications.^(a)

The cured polymer resulting from the modified formulation was different in properties than the plain butyl acrylate monomer/polymer syrup composition. The aggressive surface tack had been reduced so that the cured polymer could be handled without sticking to every surface it came in contact with and the modulus had also increased slightly, improving the handling characteristics. The cured polymer most resembles the RTV silicones in properties and may also have the advantage of being amenable to on-site repair of modules.

In addition to the modification of the cure properties of this pottant, a new production method was given a preliminary laboratory investigation. The laboratory method given to date requires several days to produce even a small quantity of syrup. The difficulty lies primarily with the production of the initial polymer that is used as the resin component of the syrup. After polymerization almost an entire day is required to remove the reaction solvent under heat and reduced pressure to yield the pure polymer. As the reaction mixture is "stripped" the viscosity rises rapidly and the rate of escape of solvent becomes slower and slower. The pure polymer also constitutes a problem because it must be redissolved in monomer. This is also a slow process, requiring stirring overnight. Heat must be avoided during the redissolving stage in order to prevent premature polymerization of the monomer.

A new method for the production of the poly butyl acrylate syrup was explored. Instead of degassing the reaction mixture to "dry" polymer before the addition of the monomer diluent, the monomer was added while the cyclohexane solvent was still present. The entire solution was then vacuum stripped to give the final solution of 35% polymer solids in butyl acrylate

(a) LSA Project Document No. 5101-83, Block IV Solar Cell Module Design and Test Specification for Residential Applications, Nov. 1, 1978, Jet Propulsion Laboratory.

monomer. The rationale for this approach is that the cyclohexane has a very much higher vapor pressure than the monomer and degasses from the solution before any monomer is lost.

The vacuum stripping of the cyclohexane solvent from the completely formulated syrup is currently envisioned as the production method of choice. A plant scale wiped film has extremely high stripping efficiency, low residence time, high product throughput and can be used in a continual production process. A flow chart of the anticipated production process is shown in Figure 4, of the appendix.

Research and evaluation samples of the butyl acrylate syrup are available from Springborn Laboratories, Inc.

C. Aliphatic Polyurethanes

Urethanes have been of interest in the liquid casting type of solar module encapsulation for a number of years. They are typically two part liquid systems that cure to transparent solids after mixing. The time required for cure is temperature dependant and is also limited by the pot life of the system. Urethanes may be formulated to have cured physical properties ranging from hard and tough to extremely soft and flexible. A wide range of chemistries are available for both parts, the isocyanate and the polyol (parts "A" and "B").

Due to the application in solar modules, some desirable characteristics may be specified as the mixed syrup and the subsequently cured material. The mixed syrup must be pumped into a preformed cavity holding the cells and consequently must be low enough in viscosity not to disrupt the cell arrangement; the cure characteristics (time and temperature) must be appropriate to the fabrication process and must yield good throughput or production rates; the cured modulus must preferably be below the 2,000 psi level to provide protection to the cells at a "no thickness requirement" level; the chemistry should be aliphatic (not aromatic) in order to have optimum resistance to ultraviolet light and outdoor exposure; the cured resin should have no glass transition (T_g) within the temperature range of operation (-40°C to $+90^{\circ}\text{C}$); and the components should be pure and solvent free. These properties are the most important, although the list could be extended considerably. This list of properties may be considered as the criteria for the selection of candidate commercial materials for this application.

The aliphatic urethanes were surveyed due to the general interest in this area and manufacturers were contacted to answer the following questions:

- (1) What grades are available that are aliphatic, pourable, and solvent free?
- (2) What catalyst systems are available and what is the range of cure conditions?
- (3) What is known about the stabilization of urethanes and what additives are recommended for thermal/oxidative and UV protection?

Specific companies contacted included Mobay Chemical Co., H. J. Quinn Co., Henkel Corporation, Morton Chemical Company and Upjohn Chemical Company. Information on stabilizers was also obtained from Borg Warner, American Cyanamid and Ciba Geigy. Henkel, Upjohn and Morton Chemical Companies offer no commercial aliphatic systems that would be usable in this application. Mobay has no off-the-shelf products that could be used, however they showed interest in having a meeting at Springborn in the future to discuss the requirements more fully and possibly offer a specialized product for this purpose. They suggest that products could result based on their Desmodur L-2291A (fully hydrogenated methylene diphenyl diisocyanate) or from adducts employing hexamethylene diisocyanate (HMDI).

Only two suppliers of potentially usable systems were identified in this search, H. J. Quinn Company, Malden, Mass. and Development Associates, Inc., Kingstown, Rhode Island. H. J. Quinn offers only one commercial product designated Q-621/Q-626 (for the isocyanate and polyol, respectively). This system has the following properties:

MIXED SYRUP

Viscosity at room temperature	3,000 cps
Pot life, 70°F	3 Hours

CURED RESIN

Tensile strength	9,000 psi
Ultimate elongation	300 psi
Total integrated transmission	89 %
Color, slight yellow	
Hardness, Shore A	65
Cure requirement	2 Hours/95°C
Specific gravity	1.03
Cost: (mixed)	appx. \$1.25/lb. 0.6¢/ft ² /mil

Plaques of the Quinn Q-621 urethanes were prepared and exposed to RS/4 radiation conditions in order to determine its stability in comparison to other candidate pottants. The unprotected specimens were found to be badly degraded after 1000 hours and flowed to diffuse shapes of dark yellow/brown color. The protected urethanes survived the remaining test periods, however, deterioration of the physical properties indicates that the degradation process is still in operation. Glass provided the best stability to the urethane at the 240 day exposure period, the tensile specimens retaining 960 psi of tensile strength and 440% elongation. The specimens behind Korad film lost about 90% of the original tensile strength and the urethane behind Tedlar film discolored and flowed completely to destruction.

During the survey of industrial compounds some good input was obtained concerning stabilization of aliphatic urethanes. Mobay and Ciba-Geigy both recommended the same system as follows: 0.5 phr Tinuvin 770, 0.5 phr Tinuvin 328, 0.1 phr Irganox 1010. This is thought by both companies to be a synergistic combination that has a minimal effect on the cure of the resin. American Cyanamid offered a different formulation: 0.5 phr Cyasorb UV-5411 (a benzotriazole) with about 0.1 phr of Cyanox 1735, a phenolic/phosphite combination as the antioxidant.

Attempts to incorporate these stabilizers into the Q-621 system were not effective. In all cases it was found that each of the recommended stabilizers was sufficiently chemically reactive with the components of the mixed urethane system to severely inhibit the cure mechanism and also result in the production of bubbles.

An additional difficulty experienced in the laboratory use of the pourable urethane systems has been that of moisture reactivity with consequent bubbling of the pottant. Experimental modules prepared at Springborn all showed difficulty in this respect and no modules could be prepared without small bubbles appearing. Modules prepared with hardboard substrates were conspicuously the worst due to the hygroscopic nature of the wood fibers.

A series of specially formulated prototype encapsulation syrups were prepared by Development Associates, Inc. and were subsequently evaluated for cure requirements and physical properties. The casting syrups are two-part

liquid 100% active urethanes and require the usual type of procedure involving mixing under low shear conditions for several minutes and then degassing under vacuum. The three formulations supplied are designated: Z-2211, A-2341 and Z-2351, and find commercial use as bottle coatings and over-coatings on decorative emblems in automotive use. All are claimed to have outstanding weatherability and to date have endured six years of outdoor exposure with no additional protection. All three appear to have fast gel times, in the order of 10 minutes at 30°C, and have recommended cure temperatures of 65°C-120°C.

Cured films were tested for certain properties, the results of which follow:

	<u>Z-2211</u>	<u>Z-2341</u>	<u>Z-2351</u>
Tensile strength ASTM D-638, 25°C	3,600 psi	1,690 psi	2,750 psi
Ultimate elongation ASTM D-638, 25°C	200 %	240 %	200 %
Modulus, Young's or tangent ASTM D-638, 25°C	1,130 psi	467 psi	635 psi
Gel time: 25°C (mixed)	15 min	12 min	12 min
38°C	7 min	4 min	4 min
Brookfield Viscosity: Mixed, 25°C, RVT #2 50 rpm	appx. 500 cps	appx. 175 cps	appx. 165 cps
Cure rate, 65°C	7 min	5 min	5 min
Hardness: Shore A, 23°C (Shore D)	60	65-75	65-75
Specific Gravity, 25°C	1.07	1.04	1.04
Total integrated transmission: ASTM E-424-A	91 %	90.4 %	88.7 %
UV cutoff wavelength	360 nm	360 nm	350 nm
Glass transition temperature	appx. -30°C	-10°C	-4°C

Cured specimens of these resins are water white and very clear in appearance. The bubbling difficulties experienced with other urethane compounds when cured in the presence of moist air do not appear with these products. The manufacturer claims that the catalyst system that they use does not favor the isocyanate-water reaction that results in the presence of CO₂ bubbles in plaques cured under high humidity conditions. Small two-celled modules have been prepared with these syrups with no difficulties.

The manufacturer also claims that these candidate potting materials are completely formulated with UV screeners, antioxidants, etc., so that no further formulation work is being considered by Springborn at this time. Formulations similar to these have also been used for coatings applied to automobile vanity strips and consequently have a successful history of outdoor performance.

Recent laboratory experiments with module building show that these urethanes are easy to mix and pour due to their low viscosities and that bubble-free castings are fairly easy to prepare. A current limitation is that the mixed pot life is very short, about 15 minutes. The mixed system must be degassed and used in fabrication within this time. Development Associates claims that the cure time may be easily controlled by reformulation and that the pot life may be increased to hours if necessary.

Of the materials evaluated to date, Z-2211 is recommended for trial encapsulation studies. Its low modulus, high transparency and low glass transition temperature make it a usable first-cut formulation. Encapsulation materials from Development Associates, Inc. will continue to be developed and evaluated within the next year's work.

V. GASKET MATERIALS

Gasket materials were surveyed for use as the supporting edge and carrier of the photovoltaic module when deployed in the field. The selection of appropriate materials for this application was initially based on the inherent and well known properties of elastomers. The first criteria of consideration being compression set, low temperature flexibility, weatherability and low cost. The properties of elastomeric materials were reviewed in general and resulted in rejections and first tier candidates:

<u>Elastomers rejected</u>	<u>Reason</u>
Natural rubber	Poor weatherability
Styrene/butadiene rubber	Poor weatherability
Butyl/halogenated butyl rubber	Poor weatherability
NBR	Poor weatherability
Polysulfide rubber	Staining
Fluoroelastomer	Very high cost
Hypalon	Low temperature flex and cost

<u>Elastomers selected for further evaluation</u>	<u>Reason</u>
Neoprene	Good weatherability
Ethylene/propylene rubber (EPDM)	Good weatherability/cost
Ethylene vinyl acetate	Good weatherability/cost
Silicone	Good weatherability

A useful document was also discovered through a literature search on materials suitable for solar module applications, entitled "Collector Sealants and Breathing". This was a study recently (February 1980) completed by Westinghouse Electric Corporation, Pittsburgh, PA, concerning the performance of elastomer gaskets and sealing compounds for use in solar thermal collector cells. In this study a wide variety of commercial compounds were evaluated in laboratory testing for properties such as ultimate elongation, compression set, hardness and the changes in these values after thermal and hygroscopic aging.

Compression set is seen as a critical property for the performance of elastomer gaskets. The weight of the module in the gasket when mounted at an angle applies a compressive load to the bottom of the gasket. If the rubber in this location creeps, compresses or otherwise changes its physical dimensions, the module will become loosely held in the frame and may become prone to damage. Compression set is a standard measurement of the elastomers resistance to deformation under load. The results of compression set and other tests were found in the Westinghouse report and appear in Table 8 in the appendix. A summary of the compression set values is as follows:

TABLE 1
SUMMARY OF COMPRESSION SET THERMAL AGING DATA

Material	Compound	Time (days) to Reach 50% Compression Set		
		125°C	150°C	175°C
Fluorocarbon	31-323-0731	7400*	150*	135
Silicone	NPC 80/40	100	21	5
Silicone	SE 7550	50	7	2
Silicone	HS 70	33	8	2
EPDM	Nordel 3300-11	103	50	27.5
Acrylic	Hycar 4054	105	28	10.5
Ethylene- acrylic	Vamac 3300-12A	35	8	4
Butyl	8EX-123	23	8	4.5

* Extrapolation of an Arrhenius plot.

As may be seen in this summary, the fluorocarbon elastomer (Viton-DuPont) had the best compression set properties of the materials tested, followed by EPDM and then acrylic and silicone elastomers. Although not shown on the table, one of the difficulties experienced with the fluoro-elastomers is that of low temperature compression set, a characteristic that could present problems in geographic areas where severely cold winters are experienced. In terms of thermal aging the silicones are unquestionably

superior to all other elastomers, however their compression set values are low. The Westinghouse report contains recommendations for elastomers for this application that are believed to be viable candidates for both high and intermediate service applications, as follows:

1. High temperature (over 150°C)
 - . Fluorocarbons
 - . Silicones
2. Intermediate temperature (below 150°C)
 - . Acrylics
 - . Acrylic copolymers
 - . EPDM

The one physical property which limits service lives of elastomers most severely is elevated temperature compression set. Most promising approaches toward improving this characteristic involve moderate increase of cross-link density and increase of filler content.

The fluorocarbon rubber and the polyacrylic in particular suffer from excessive compression set at low temperatures. This difficulty is associated with the development of crystallinity during low temperature exposure. An approach to correction of this problem involves modification of the polymer chains in such a manner as to decrease regularity in the chain. This objective might be achieved by introduction of an additional monomer which can be copolymerized into the growing chain at random intervals. Other possibilities involve use of polymer blends or alloys and IPN (interpenetrating networks). An approach certain to be effective at reducing low temperature crystallinity involves incorporation of certain high molecular weight plasticizers, however this then presents problems with migration.

These properties and recommendations were then compared on a cost per pound basis. Typical gasket formulations were selected and costed out on a formulated cost per pound basis (see Table 11, appendix). The following table gives the comparison:

COST vs. COMPRESSION SET RECOVERY

Compounded Elastomer (Typical Formulation)*	Comp. Set Range (%)	Set Recovery Range (%)	Compound Cost (\$1/lb)	Cost/Set Recovery Index
EPDM	10-30	90-70	0.58	0.64-0.83
Neoprene	15-25	85-75	0.87	1.02-1.16
EVA	20-35	80-65	0.85	1.06-1.31
Silicone	10-35	90-65	2.53	2.81-3.89

Compression set will vary tremendously depending on the characteristic of the individual compound. Different fillers and filler loadings will be responsible for this variation. Values listed are representative of typical formulations. The cost/set recovery index number was obtained by dividing (% set recovery/100) into cost per pound of compound. Lower values indicate better value regarding compression set-cost performance.

In conclusion, EPDM elastomers are thought to offer the overall best combinations of properties to give optimized cost/performance values. EPDM offers: (1) the best compression set/cost ratio; (2) low compound cost; (3) the ability to tolerate high loadings of fillers; (4) low gum stock cost; (5) easy processability and extrusion; and (6) proven weatherability.

The automotive industry also appears to be in agreement with these conclusions in the use of weatherstripping:

- . EPDM is the dominant elastomer used for automotive weatherstripping. Several industry sources indicate that at least 90% of the domestic automotive weatherstripping is EPDM with the remaining 10% being manufactured with Neoprene, Noreosorex, and blends. There is some variation depending on whether dense weatherstripping or sponge weatherstripping is being considered.
- . A typical weatherstripping formulation includes approximately 20-30% by weight EPDM polymers. This percentage will produce a compound which has a tensile of approximately 1000-1500 psi. Usually, an automotive weatherstripping has a durometer value of 60-70 Shore A.
- . In total, approximately 36 million lbs. of EPDM was used to manufacture domestic automotive weatherstripping in 1979.

The fact that EPDM has been used successfully by the automotive industry for long periods of time is an encouraging point. A history of performance of this material in a related application is well documented and 20-year life has been demonstrated.

A survey was conducted into the sources of EPDM elastomers and companies with the capability to supply finished goods for this application. The manufacturers of EPDM are as follows:

<u>Manufacturer</u>	<u>Product Name</u>
Uniroyal	Royalene
Copolymer Rubber & Chemical Corp.	Epsyn
E.I. DuPont de Nemours	Nordel
Exxon	Vistalon
Goodrich	Epcar

These companies are only gum stock suppliers, however, and not compounders or fabricators. The number of commercial compounders numbers in the hundreds and the fabricators number in the thousands.

A survey was therefore undertaken to identify companies supplying gaskets specifically for the solar industries. Nine companies were found to be of assistance in this area.

All of the companies listed below were contacted and expressed an interest in our gasket problem. All have compounding and extrusion facilities for EPDM gasketing. Most have techniques for providing molded-in corners for gaskets. Companies are listed in order of probable success/experience based on telephone conversations.

Potential Gasket Suppliers

Pawling Rubber Co.	Pawling, NY
Sperry Rubber & Plastics Co.	Brookville, IN
Johnson Rubber Co.	Middlefield, OH
Carlisle-Georgia	Middlefield, OH
Smaller-Globe Corp.	Portland, IN
General Tire & Rubber Co.	Akron, OH
Globe Rubber Works	Rockland, MA
Garlock, Inc.	Palmyra, NY
Delford Industries, Inc.	Middletown, NY

Contacts with the more important of these suppliers is summarized as follows:

Pawling Rubber Co. - Pawling, NY (914) 855-1000

Pawling has a line of gasket material, both compounds and finished cured gasket materials in both EPDM and silicone. It is claimed that they currently supply 90% of the solar collector industry with gaskets-

Compounds are extruded and the corners are injection molded into the stock to fit the panel dimensions. Gaskets are then cured and snapped into place on the panel like a rubber band. The gaskets must be sized for the job giving the process a specialized nature, but this eliminates the need for cutting, mitering and gluing which can be a messy job. Steve Smith should be contacted for applications.

Garlock, Inc., Palmyra, NY (315) 587-4811

Garlock both formulates and processes gasket/weatherstripping material. They have several EPDM compounds (60-70 Shore A) which they feel might be appropriate. They have the facilities to provide extruded cured gaskets of the desired profile.

Delford Industries, Inc., Middletown, NY (914) 342-5805

Delford can supply an extruded rubber profile to meet any design specifications we can come up with. They do not do the "molded in corners" but they can cut and splice to supply a finished gasket.

Sperry Rubber and Plastics Co., Inc., Brookville, IN (317) 647-4141

Sperry has had past experience in producing gaskets for the solar industry. They have their own laboratory for formulation, compounding, and processing. They are quite versatile: can supply extruded cured channel gasket cut/mitred corners, can splice in vulcanized 90° corners, or can do injection molded corners (like Pawling).

Globe Rubber Co., Rockland, MA (617) 871-3700

Globe can do compounding and profile extrusion to meet module specifications. They are somewhat unclear on complete gaskets (corners may be a problem for Globe) but are interested in seeing blueprints for a final design to determine what they can do.

Sheller Globe Corporation, Portland, IN (219) 726-8171

They claim this type of gasketing is not problem. They do compounding, extrusion, and corners. They asked if the design of the panel could be modified to put a 3" radius on corners so that the expense of the corner addition could be saved. Future contacts should go through Larry Wilcoxson in Portland, IN.

Johnson Rubber Co., Middlefield, OH (216) 632-1611

Johnson is presently involved in solar gasketing for a variety of companies. They have complete compounding and extrusion facilities and are familiar with the corner production methods. They appear quite interested in solar application and work with all materials except silicones. Contact: George Krupa.

General Tire and Rubber Co., Akron, OH (216) 753-5131

They claim that CT is involved in this area with most of the custom extrusion being done at their plant in Arkansas. Contact: Al Hoffman, Plant Manager (501) 793-3179.

Carlisle-Georgia, Middlefield, OH (216) 32-1671

Carlisle-Georgia is familiar with solar gasketing and does considerable custom extrusion. They appear quite interested in development of a gasket material (Note: they have worked with collector panels and PV panels). Contact: Bob Connors.

Uniroyal: (203) 723-3000

This company makes a tubular extrusion designed to act as the collector pipe in solar thermal panels. The heat transfer fluid circulates directly through the tubing. This and other solar related rubber products are based on their Royalene elastomer stock. Contact: Al Crepeau (203) 723-3825.

All of these contacts are promising suppliers for custom molded gasketing for solar energy related applications and are aware of the performance/formulation relationships related to long term service in outdoor environments. A representative sample of manufacturers product literature (Pawling Rubber Co.) and comparison of product specifications and design application are given (Tables 12 and 13) in the appendix.

An additional piece of information is also felt to be useful with respect to this study. An ASTM specification for the selection of solar gasketing materials has been written. This specification, entitled "Rubber Seals Used in Flat Plate Solar Collectors (ANSI/ASTM D-3667-78), relates to test procedures, properties, classes and specifications for the appropriate selection of solar gasket and sealant material and is reproduced in its entirety (Table 14) in the appendix.

VI. SOLAR MODULE SEALANTS

Sealants are required to seal the edge of the photovoltaic module between the module edge and the rubbery gasket surrounding it. The sealant must have the following properties: (1) adhesive to both surfaces; (2) compliant and mechanically forgiving; (3) glass transition temperature below -40°C ; (4) serve as a barrier to liquid water; (5) applicable to the modules construction by a commercial and high volume technique; (6) have low water vapor transmission; (7) weatherable; (8) low cost. After considering these properties, two more were added, solvent-free and non-curing. Non-curing sealants are thought to be a better choice due to their ability to be somewhat mobile along the gasket/edge interface and therefore impart a "self-healing" characteristic to the edge. Solvent-free is also desirable to prevent attack of the module edge and absorption by the pottant layer.

Major manufacturers of sealants were identified and contacted for products having the desired properties. The companies contacted are as follows:

Dow Corning, Midland, MI
H. B. Fuller, St. Paul, MN
General Electric, Waterford, NY
Gibson Homans, Twinsburg, OH
Goss and Goss, San Francisco, CA
Henkel Corp., Minneapolis, MN
Inmont Chemical, New York, NY
3M Company, St. Paul, MN
Mortell, Kankakee, IL
Polymeric Systems, Inc., Pottstown, PA
PRC, Glendale, CA
Swift Adhesives, Chicago, IL
Tremco, Cleveland, OH
Pecona Chemical Corp., Harleysville, PA

From these contacts a general survey of sealant compounds and manufacturers resulted and has been tabulated in Table 15.

This list of materials was then reduced further to refine the selection of suitable compounds. These sealants were first compared on the basis of generic chemical class and cost, as follows:

SEALANT USAGE COSTS

<u>Generic Class</u>	<u>Appx. Cost/Lb.^(a)</u>	<u>Est. Cost/Module^(b)</u>
Silicone	\$2.25 - 4.50	\$ 0.50
Polysulfide	2.25 - 5.70	0.27 - 0.68
Polyurethane	2.08 - 2.70	0.28
Polyamide	2.30 - 2.80	0.30
Acrylics	1.00 - 2.40	0.24
Butyls		
Hot melts	1.62	0.19
Tape compounds	3.67	0.44
Non-cure hot melt	2.00	0.24

(a) High volume, non-specialty application

(b) Costing basis: for a 1.2 m x 2.4 m module of appx. 280 W power output. Assume 1/8" (3 mm) round bead around edge: volume of sealant required, 58 cm³; assume specific gravity = 1.00: weight required appx. 58 gms, or 0.12 lbs.

Additionally, materials performance information has been tabulated according to the chemistry of available sealant compounds, as follows:

Relative Performance - Various Sealant Base Materials

	Joint Movement Tolerance		
	Small (up to $\pm 5\%$)	Moderate ($\pm 5\%$ to $\pm 12\%$)	Large ($\pm 25\%$)
Polymeric Base	Drying Oils Polybutenes Bitumens Neoprene	Butyl Acrylics Hypalon	Polysulphides Silicones Polyurethanes
Service Life	Up to 5 years	10 years min.	15 to 20 years
Cost	Low	Low to Moderate	High

Source: Adhesives Age: February, 1980, p. 34

It should be noted with respect to the preceding tables that the compounds used for representative pricing are not necessarily usable for photovoltaic module application. The prices represent typical ranges and include sealants that are water based, have high solvent content and may cure with the evolution of an undesirable by-product (such as acetic acid in the silicones).

The automotive industry has encountered the need for edge sealing for many years in windshield applications to prevent the penetration of water between the glass and the gasket.

The automotive industry used solvent based sealant systems for years, however they currently favor preformed tape, low solvent systems (under 5%) and water based sealants. Water based systems perform well once cured, but it takes much longer for the water to evaporate, hence tapes and low solvent systems are used when possible.

General Motors' use of sealants is typical of industrial trends in this area. Historically, the two component polysulfide compounds were used to caulk windshields and other weatherstripping applications. These materials

were difficult to work with and also had an objectionable odor. The butyl tape sealants gradually replaced the polysulfide systems and resulted in improved performance and faster production rates. Butyls have been the standard sealant for years, however they are now being replaced by the one part room temperature cure urethane sealants. The reason for this is that windshields now have a structural requirement that cannot be met by the lower tensile strength butyls. These new urethanes are applied as continuous beads, set on exposure to moisture, and cost twice as much as the butyls (appx. 12¢/ft.).

In addition to the requirements previously mentioned for the selection of sealants, a few other properties are also worth consideration.

Sag resistance is important. Despite the need for easy extrudability, non-sag grades must be stiff enough not to flow from vertical or overhead joints.

Hardness stability is also an important factor and refers to the corresponding increase in both the hardness and the cohesive strength of the sealant. If this increase in hardness in actual use leads to a cohesive strength greater than the adhesive strength, the bond will fail.

Bonding properties and durability are of prime consideration. The sealing properties of a sealant depend on its ability to adhere to the wall of the joint despite imposed stresses due to joint movement. This adhesion must remain strong despite exposure to harsh environments involving cyclical humidity and temperature swings.

Sealants provided in tape form present the best labor and materials cost savings, and high quality performance. These tapes are almost always based upon butyl rubber or modified polyisobutylene due to its excellent adhesion, weathering and aging properties. Preformed tapes also have an unlimited shelf life and require no special application or mixing equipment. Application is quick, easy, clean, accurate and the seal forms immediately with no cure time or solvent evaporation.

Tapes can be formulated to achieve a wide variety of properties; two general categories are low-resilients and resilient tapes. Resilience, softness, and adhesion properties are controlled by combining crosslinked butyl with regular butyl or bromobutyl compounds.

At this time, the butyl sealants appear to have the most desirable cost performance characteristics with well-documented history of use in long term field applications. Four major types of butyl sealants are commercially available. There are:

- (1) Hot melt butyl sealants (curable) - These materials are applied at temperatures of about 400°F from a heated gun. They harden on cooling to a non-tacky material with excellent (60 psi) peel strength vs. glass. Adhesion to plastics is considerably less. These sealants exhibit sag at temperatures above 150°F.
- (2) Hot melt non-hardening butyl - These are similar to butyls from which tapes are made. They are butyl rubber/isobutylene blends which have a higher butyl content than butyl caulking compounds. They have very low water vapor transmission. These compounds contain no solvent and are gunnable at raised temperature.
- (3) Butyl caulk - These are all solvent containing sealants, the solvent being necessary to impart gunnability to the sealants at room temperature. They tend to be hardening and non-tacky when cured. These compounds should be avoided due to the potential attack of the solvent on the module pottant and gasket components.
- (4) Butyl tape (cold butyl) - These are butyl/isobutylene blends pre-formed into tape. Available in various forms, and varieties from many suppliers: Tremco, Pecora, Fuller and 3M. Non-hardening and useful in -40 to 400°F range. This is the type of sealant used in windshield applications and in addition to the term "cold butyl" it is also known as "compression setting" or "non-setting" butyl. In use, this preformed tape compound is placed in the gasket channel as a long ribbon. The glass is then pressed into the channel and the seal is formed from compression. Cold butyl had excellent adhesion to glass, has no cure time, requires no special

equipment for use and is produced by the ton on a cost competitive basis. Commercial examples of this type of compound are Tremco 440 tape and 3M Company's product 5354.

Alternate to the preformed and compression fit type of application are the hot melt systems. Butyl based hot melt sealants are curable compounds that have been used extensively for the sealing of insulating windows and doors and have been found to be superior to polysulfides and other sealants in the tests conducted by SIGMA (Sealed Insulated Glass Manufacturer's Association). The hot melt materials require special systems (hot melt guns) for application; however, the material handling is somewhat easier. In the solar module industry, the channel of the preformed gasket could possibly be filled with sealant from a hot nozzle and then forced directly onto the edge of the module and permitted to set into place. Example of commercial hot melt butyl sealants are: National Adhesive product 73-6417, 3M Company's 3764 and H. B. Fuller's HM1081. The product manufactured by H. B. Fuller was tested and found to have superior adhesion and working times. (a)

In addition to looking at commercial products available we also examined commercial applications for sealants. It is not possible, as a result of the survey to date, to definitively identify a single compound or class of compounds that optimize the cost/performance characteristics required. This survey will continue with the investigation of a wide range of commercial products and history of successful applications. Additionally, laboratory evaluations will be conducted to assess product performance in simulated module conditions.

(a) MB Associates, San Ramon, California, Final report for JPL Contract No. 954882, Process Development for Automated Solar Cell and Module Production, June 30, 1980.

VII. PRIMERS/ADHESIVES

A new primer was evaluated using a formulation developed (for EVA) at Dow Corning Corp. This primer is similar in composition to the primer that has been used over the past year's activities, however it has been modified with a small quantity of peroxide. The concept employed in this formulation is that the addition of the peroxide causes a localized generation of active free radicals during the heating and curing stage and consequently gives a higher crosslink density at the polymer/substrate interface. The primer composition is as follows:

Dow Corning Silane Z-6030	90 parts
Benzyl dimethyl amine	10 parts
Lupersol 101 peroxide	1 part

Dilute the above mixture to 10% active with reagent grade methanol.

This is Springborn Laboratories primer number A11861-1. This primer is also improved by the addition of a tertiary amine (replacing Z-6020 in the original formulation) that results in better shelf life and much less color formation on aging. This new formulation turns a light pink color after storing at room temperature for 1 month as opposed to an opaque dark red resulting from decomposition encountered with the previous formulation. The mixture was tested by priming clean soda-limed glass slides with a thin layer of the primer and air drying for 15 minutes. The fully formulated EVA compound, A9918, was then compression molded and cured to the surface. The resulting specimen was then tested for peel strength by ASTM D-903. The results were excellent, showing an average peel strength of 39.6 pounds per inch of width, and a small scattering of data points. Duplicate specimens were placed in boiling water for two hours and evaluated by the same process. The average strength was found to be 27 pounds per inch of width, still excellent adhesion. A quantity of the primer formulation was prepared without the alcohol diluent and blended into the standard A9918 EVA formulation at the level of 1 part per hundred of compound to test the self-priming effect. The resulting resin (A11862) was then compression molded to a clean glass slide as before and tested for peel strength with the same method. An average strength of 35.4 pounds per inch of width resulted,

with a variation of ± 4 lbs. The specimens that had been immersed in boiling water all broke during bond strength testing without evidence of peeling.

The results are tabulated in Table 16. As may be seen in the table, the new formulation gives excellent and durable bonds to both regular soda-lime and low iron grade glass and is also effective with some metals. Aluminum primed with All861 gave an average bond strength of 41.0 pounds per inch of width peel strength and the adhesion to mild steel was even more spectacular with an average strength of 56.0 pounds per inch of width (failure cohesive in EVA). This is the highest bond strength found between EVA and any other material. Bond strengths to Tedlar and Korad were very low, however, indicating that a different chemical approach may be necessary with these materials.

This new primer is the most effective formulation tested to date for glass, aluminum and mild steel, and will be used in the fabrication of all the test modules prepared in the program that will use these construction materials.

VIII. EXPERIMENTAL AND ANALYTICAL ACTIVITIES

A. RS/4 Exposure Results

The degradation of polymeric materials in outdoor weathering is caused primarily by sunlight, especially the ultraviolet component. In actuality, the deteriorating effect of light is usually enhanced by the presence of oxygen, moisture, heat, abrasion, etc. and in many cases may be referred to as photooxidation, resulting from the combined effects of oxygen and sunlight.

Sunlight reaching the earth is filtered through the atmosphere, removing shorter wavelengths up to 290 $m\mu$ before it reaches the surface of the earth. Thus ultraviolet effects on plastic result primarily from wavelengths of approximately 290-400 $m\mu$, which are approximately 5 percent of the total solar radiation reaching the earth.

The lower the wavelength of light, the greater is its potential to produce a chemical change in material. This energy must first be absorbed, however. Plastics vary considerably in their ultraviolet absorbing properties, but few are completely transparent in the 300 to 400 $m\mu$ range. Once the radiant energy has been absorbed, the likelihood of chemical action will depend on the degree of absorption and the stability of the chemical bonds in the polymer. The induced chemical modifications are responsible for the deterioration of optical and mechanical properties and usually result in reductions of tensile strength, elongation and transparency.

These degradative effects may be simulated in the laboratory and accelerated to yield approximate predictions about long-term behavior from short-term testing. A number of devices are commercially available for this type of testing and include equipment such as "Weather-Ometer", Fadeometer", QUV, etc. One of the more popular and simple devices is the RS/4 exposure chamber. This device is a modification of standard test procedure ASTM D-1501, "Exposure of Plastics to Fluorescent Sunlamp", and is widely used throughout the plastics and other industries for the purpose of accelerated weathering. In this device test specimens are mounted on a turntable that rotates beneath a fluorescent sunlamp (General Electric RS/4 Type) in a closed chamber thermo-

stated to a temperature of 50°C. A graph of the spectral irradiance of this type of lamp appears in Figure 5.^(a)

The specimens are removed for testing at appropriate intervals based on the degradation rate of the material under examination. For the purpose of determining the relative stability of potant and outer cover formulations, a schedule of 60, 120 and 240 days exposure was used. This may also be expressed as 1440, 2880, and 5760 hours. As a point of comparison, unstabilized polypropylene is physically degraded after approximately 160 hours and unstabilized low density polyethylene is degraded after approximately 450 hours of exposure.

Outdoors, the degradation rates of these polymers varies according to their location. At Enfield, Connecticut, polypropylene with no stabilizers degrades to brittleness in approximately 8 months (5,700 hrs) and low density polyethylene fails at about 18 months (12,000 hrs). Areas where the sunlight is more intense and there are fewer cloudy days results in more rapid degradation. Exposure to higher temperatures is also significant; the degradation rate in polypropylene is almost doubled for every 10°C increase in temperature.

Due to the dependance variations in temperature and light exposure the deterioration of plastics is also location dependant. Exposures in Mexico City^(b) have been found to be about twice that of the Enfield location.

Based on these actual outdoor lifetimes, approximate correlation factors can be calculated for RS/4 to outdoor weathering. In comparing RS/4 to Mexico City, for polypropylene the acceleration factor is approximately x18 and for polyethylene approximately x13. Although these acceleration factors provide a useful basis of comparison, it should be remembered that considerable variations may be found between different outdoor locations and/or simulated weathering conditions. Factors affecting the degradation rates include specimen thickness, spectral distribution, heat history, additives, temperature, polymerization catalyst impurities, etc.

(a) Estey, Roger S., "Measurement of Carbon Arc and Sunlamp Sources at Dow Corning and Springborn Laboratories" Jet Propulsion Laboratory IOM 341-78-43, [REDACTED]

(b) Springborn Laboratories information resulting from a program concerning the Weathering Degradation of Polyolefins.

During the past two years, a continuing series of specimens have been placed under RS/4 accelerated exposure, and evaluated for mechanical or optical properties, or both, after completion of the exposure intervals indicated. The specimens under exposure have consisted of variations in EVA formulations to determine the effects of additives on the stability, samples of Korad and Tedlar outer cover films, polyurethane and EMA pottants, and an experiment with protective absorbing films over polypropylene.

A number of materials have been evaluated after 5,760 hours (8 months) of RS/4 sunlamp exposure. This set included two EVA formulations, one being A9918 formulation currently in use as the industrially ready pottant and the other a specialty formulation prepared with 5-vinyl tinuvin UV absorber reacted in during cure. Both formulations show no signs of discoloration or physical degradation and the properties measured within about 10% of control values. Due to the typical scattering of points that is found with the mechanical testing of elastomer., this is felt to be within acceptable experimental error and does not indicate any significant degree of degradation. Formulas of EMA resin had greater variations. Specimens of the natural uncompounded resin, Gulf "Polyeth 2205", were degraded to the point of not being amenable to testing. Although the specimen showed no visible signs of change, such as coloration or lack of flexibility, the polymer had become sufficiently "cheesy" through chain scission that it could not be clamped in the mechanical tester. Formulations of EMA with the peroxide crosslinking agents and no other ingredients were exposed for the same period of time to assess whether peroxide sensitization took place and if crosslinking would improve endurance to this type of environment. Both peroxides improved the performance of the EMA. Although both had become softer and developed signs of cracking on the surface, the specimens retained sufficient properties to be tested. Both had tensile strengths in the order of 400-500 psi and elongations of 35%-45%. No signs of coloration were noticed in either of these specimens. The fully formulated EMA, compound A11877, showed little change in any properties over this exposure period except that the elongation had almost doubled, from 640% to almost 2000%. The tensile

strength also showed a small increase of 17%. These properties are still quite usable for the pottant function in modules.

Candidate outer cover films were also assessed for resistance to RS/4 radiation.

The results of the 3M acrylic film designated X22417 have been obtained after an 8-month (5,760 hour) period of exposure. The film was found to have an elongation of approximately 6%, a tensile strength of 15,000 psi and an apparent modulus (at break) of 6.3×10^5 psi. Although the tensile strength has dropped to 60% of its original value, the specimen is still clear, colorless and flexible. It is thought that the decay in this property may be due to stress relaxation of the oriented film rather than chemical degradation. This speculation may be tested later by measurements of solution viscosity or GPC analysis for molecular weight distribution.

Another promising candidate, Tedlar 100BG30UT vinyl fluoride film, has survived 5,760 hours of exposure and was found to have an elongation of 78%, a tensile strength of 16,200 psi and an apparent modulus of 2.5×10^5 psi. These values vary little from the control, consequently the film appears to be surviving virtually unchanged.

An early prototype formulation of EVA that has been under RS/4 exposure for 22,000 hours was removed for physical testing. Only a single tensile specimen was evaluated due to the small amount of test sample remaining. No change in the properties of this material is evident from mechanical and optical testing. Summaries of the ongoing exposures are shown in tabular form in Table 17 of the appendix.

A series of polyethylene and polypropylene tensile bars are being evaluated for tensile strength, elongation, yield stress, and yield elongation after known exposure times under RS/4 radiation. The purpose of this experiment is to obtain data that may be used in the preparation of a log property/log exposure time chart that will hopefully yield a linear plot indicating a uniform reaction rate. This first-order Arrhenius reaction when plotted should yield a slope which will more accurately "calibrate" the acceleration factor of the RS/4 exposure. Polyethylene and polypropylene will be used as reference polymers to which other materials

may be compared. The same method, if successful, will be used to "calibrate" the CER reactors provided by JPL as part of the test program, and also the outdoor exposure conditions.

B. Thermal Analysis

Solar modules in field operation are exposed to the potentially damaging conditions of weathering that include heat, humidity, rain, frost, solar ultraviolet, etc. The module and any directly exposed components must be able to resist these elements for the projected life of the module, a minimum of twenty years. The encapsulation package is intentionally constructed so that components that are sensitive to one form of degradation are protected by another that is not adversely affected. For example, pottants that may have a sensitivity to ultraviolet light may be protected by either glass or absorbing outer cover films.

One condition that will affect all the components of the module, however, is heat. Modules under field operating conditions may reach temperatures in the order of 50° to 70°C , and in the event of cell "hot-spotting" temperatures could reach an extreme of 120°C . In addition, the module and its components have to tolerate the cycling effects between the thermal extremes of day and night.

Due to their chemical nature, pottants may potentially be the components most severely affected by heat. In order to examine the inherent thermal stability of these materials a technique known as differential thermal analysis was performed on some of the pottants of current interest in this program.

Differential thermal analysis is a method that determines thermal transitions in the test material as a function of temperature. In practice, a small (approx. 20 milligrams) sample of the test material is placed in a micro-crucible that is intimately in contact with a thermocouple and contained inside a heating cavity. The output of this thermocouple is referenced to a second thermocouple, also within the heated chamber. The differential output of the two thermocouples is recorded on a piece of graph paper and indicates heat absorption or evolution (endotherm or exotherm) of the sample as a function of oven temperature. The resulting record is called a thermogram and shows every physical or chemical change in the sample

that absorbs or releases energy. The area integrated under the peak is proportional to the amount of energy absorbed or released. Thermograms yield useful information about heats of reaction, reaction rates, activation energies, etc. With respect to polymers, specifically, DTA may be used to determine the glass transition temperature (T_g), temperatures and heats of fusion, cure rate and temperature and the effects of catalysts and stabilizers. DTA in air has the advantage over TGA (thermogravimetric analysis) in air in that it shows the earliest temperature at which an exotherm due to oxidation starts. This preceeds weight loss sometimes by as much as 100°C .

DTA was employed in this program to examine the thermal and thermal/oxidative stability of some of the candidate pottant compounds. Samples of base resins were run to indicate the inherent stability of the polymer itself and fully compounded and cured samples were also run to determine the effect of additives and crosslinking. Additionally, duplicate runs were performed in atmospheres of both air and nitrogen to differentiate between thermal degradation (pyrolysis) and oxidation reactions. All thermograms were run at a low rate of temperature rise ($10^{\circ}\text{C/minute}$) to obtain accurate onsets of transition. The results are shown on Table 18.

In most cases, two peaks (both exothermic) were found on the thermogram. The first peak is felt to be predominately due to the oxidation or volatilization of compounding ingredients and the second is that of polymer decomposition itself.

The first material studied was Elvax 150 (DuPont), the base resin used in the preparation of the EVA potting compound currently being produced for module encapsulation. Ethylene vinyl acetate undergoes thermal degradation to split out one mole of acetic acid for each mole of vinyl acetate present in the polymer and often thermal analysis (TGA) is used for the quantitative determination of vinyl acetate in EVA polymers. The onset of acetic acid loss is also affected by the presence of air oxidation and preceeds at a lower temperature than in an inert atmosphere. This is due to localized self heating of the specimen from the simultaneous oxidation process and accelerated decomposition. This is typical of olefin polymers, most of which begin to oxidize in the range of 200°C to 250°C . In air the Elvax 150 begins to show acetic acid loss at an onset temperature of about 200°C , and in nitrogen it begins at about 340°C . The cured and

compounded EVA, number A9918, gives similar results and shows no apparent improvement in thermal stability, either in air or nitrogen.

The results obtained for EPDM, a candidate pottant of previous consideration, are similar to those obtained with EVA. The onset of oxidation upon heating in air is 210°C , typical for an olefin of this type. Due to the presence of unreacted double bonds that evaded the curing process, the oxidation proceeded readily and at a lower temperature than may be expected in a saturated polymer. In nitrogen, the first peak at the lower temperature is absent (in comparison to EVA) due to the absence of vinyl acetate or any other group prone to thermal decomposition.

The results obtained from these first two pottants of interest were compared to two of the materials currently being used on an industrial basis for the fabrication of solar modules. The first of these to be examined was polyvinyl butyral ("Saflex" PT-10, Monsanto). This material appears to be more sensitive to oxidation in air than the compounds previously examined. The onset of exotherm occurred at 175°C and continued gradually up to 240°C at which point the oxidation was so extensive that the instrument overranged, sending the recorder pen off the chart. In the absence of air (nitrogen atmosphere) the compound is much more stable giving an exothermic peak at 365°C . This is still below the pyrolysis peaks found for the other materials, however. Overall, the PVB has the lowest thermal stability of the candidate pottants examined to date. The other commercially used pottant tested was the room temperature vulcanizing silicone rubber. Sylgard 184 (Dow Corning). In contrast to the PVB, and all the other materials, Sylgard had conspicuously the highest resistance to thermal degradation. In air, the silicone showed one small oxidation peak at 300°C and in nitrogen no decomposition or thermal excursion could be noticed in the range of room temperature to 500°C .

Some of the newer pottants under consideration were also run. Ethylene methyl acrylate (EMA) was examined, both as base polymer and compounded formulation. The results were typical for olefin polymers, with an oxidation peak appearing at about 215°C and pyrolysis onset at around 400°C . Both compounded and base resin formulations gave similar spectra. A conspicuous advantage with EMA is the absence of acetic acid or some

other small molecule splitting out due to thermal decomposition. In a nitrogen atmosphere no thermal effect is noticed until 420°C is reached. The polybutyl acrylate pottant (cured) was also evaluated by DTA and gave results that appeared to be similar to the other pottants when run in air. The small peak occurring at 207°C , typical of the polyolefins was also found in a nitrogen atmosphere, however, and is obviously not an oxidation reaction. This peak is also very small when compared to the thermograms of olefin oxidation, and indicates that some other type of reaction is occurring. This reaction could be due to further crosslinking, decomposition of peroxide residues, polymerization of trace amounts of monomer or some other reaction. Pyrolysis proceeds at approximately 380°C in both air and nitrogen. Apart from the small unexplained exotherm at 206°C , this material appears to be quite oxidation stable.

From examination of the DTA curves of the candidate pottants tested so far, EMA is probably the most desirable of the sheet lamination extrudable compounds. EVA copolymer has the weakness of loss of acetic acid upon heating and EPDM oxidizes rapidly due to the presence of residual unsaturation in the polymer backbone. EMA has neither of these deficiencies that could possibly result in degradation difficulties during long term exposures. The main consideration of any member of the olefin polymer family may be the poor oxidation resistance. Antioxidants are usually essential for any member of this group, especially under long term exposure to elevated temperatures. Only one candidate casting resin, polybutyl acrylate, has been examined so far and the results appear encouraging. With the exception of one very small unidentified peak of 206°C the material appears to be very resistant to thermal oxidation and is stable to almost 400°C .

Although DTA is useful for revealing the onset of thermal reactions in polymers and provides a ranking of compound stability a problem still exists with knowing how much thermal stability is required in a polymeric material used as a solar module pottant. The onset of oxidation or thermal decomposition in the formulations observed appears at temperatures over one hundred degrees above the nominal operating temperatures at which the modules are intended to operate; however how a pottant will actually survive in terms of field deployment will probably have to be determined by field trials followed by property analysis.

C. Soil Resistant Coatings

The performance of photovoltaic modules is adversely affected by surface soiling, and generally, the loss of performance increases with the quantity of soil retained on their surfaces. To minimize performance losses caused by soiling, photovoltaic modules not only should be deployed in low-soiling geographical areas, but also should have surfaces or surfacing materials with low affinity for soil retention, maximum susceptibility to natural cleaning by winds, rain, and snow; and should be readily cleanable by simple and inexpensive maintenance cleaning techniques.

The action of soiling is considered to include accumulation, natural removal by wind, rain, and snow; and activation of mechanisms that result in surface soiling that resists natural removal, thus requiring maintenance methods.

The theoretical aspects of soiling have been addressed recently in documents produced by the Jet Propulsion Laboratory^(a). The basic findings of these studies show that the rate of soil accumulation in the same geographical area is material independent and that rainfall functions as a natural cleaning agent. The effectiveness of the cleaning effect of the rain is material dependant, however.

A series of pottants and glazing materials were placed on the roof of Springborn's facilities in Enfield, Connecticut. As may be seen, soil accumulation occurred in all cases, with the soft silicone elastomers being the worst.

(a) Cuddihy, E. F., "Encapsulation Materials Status to December 1979" LSA Project Task Report 5101-144, Jet Propulsion Laboratory, Pasadena, CA., January 15, 1980.

Hoffman, A.R., and Maag, C.R., "Airborne Particulate Soiling of Terrestrial Photovoltaic Modules and Cover Materials", Proceedings of the Institute of Environmental Sciences, May 11-14, 1980; Philadelphia, PA.

<u>Material</u>	<u>% Transmission (a)</u>		
	<u>Control</u>	<u>4 Weeks</u>	<u>8 Weeks</u>
Pyrex Glass	92	90	90
Soda Lime Glass	87	84	87
Tedlar 100BG3OUT	84	72	77
RTV 615	79	65	65
Q1-2577	74	65	64
Sylgard 184	82	81	54

(a) Direct transmission from 350 NM to 900 NM

Based on the postulated mechanisms for soil retention on surfaces, certain characteristics of low-soiling surfaces may be assumed. These are: (a) hard, (b) smooth, (c) low in surface energy, (d) chemically clean of water soluble sales, and (e) chemically clean of sticky materials. It is possible cost effective coatings having these required properties may exist that may be applied to solar module surfaces and result in low maintenance costs and preserve the effective generation of power from these devices. A number of candidates were identified and a soiling test program was established at Springborn Laboratories, Inc.

A series of specimens for the evaluation of soil resistant surface treatments were prepared and deployed on the roof of Springborn Laboratories' facilities in Enfield, Connecticut for outdoor exposure. The specimens consisted of glass squares of 3" x 3" dimensions. Some of the squares were "Sunadex" low iron glass, the others were plain soda-lime glass used as carriers for polymeric films that had been surface treated. These organic films were held in place on the glass carriers with an adhesive.

The adhesive used for attaching the films is a non-curing solvent based pressure sensitive of acrylic chemistry. This material is produced by Uniroyal Chemical Company and called Royal M6112. It has the features of peel strength and creep resistance at both low and high temperatures, good adhesion to glass, clear and highly transparent, high surface tack and excellent UV resistance. This adhesive is used by depositing a thin (1-3 mil) layer on glass, drying in an air oven, drying in a vacuum oven

and then applying the film with a press. The film traps very little air with this technique and is then treated with the anti-soiling coating directly.

The substrates under examination are "Sunadex" low iron glass, Tedlar 100BGOUT film (DuPont) and X-22417, a biaxially oriented acrylic film produced by 3M Corporation. The surface treatments applied to these substrates are:

1. L-1668, a proprietary fluorosilane compound produced by 3M Corporation
2. L-1668 following treatment of the surface with ozone activation (for the organic films only)
3. Dow Corning E-3820-103B, an experimental treatment consisting of perfluorodecanoic acid coupled to a silane
4. The E-3820-103B following surface treatment with ozone to create active sites on the organic polymer films
5. Glass resin 650, produced by Owens-Illinois
6. SHC-1000, a silicone based hardcoat resin produced by General Electric
7. WL-81 acrylic resin produced by Rohm and Haas.

Ozone treatments are not used with the glass because no surface activation occurs in this case.

Specimens of glass and polymers coated with the liquid glasses developed at ICI/University of Delaware are also included in the test scheme. These include soda-lime glass and acrylic panels coated with chromium phosphate, iron phosphate and titanium dioxide film.

All the completed specimens were measured for power transmission using a specially designed standard cell device. This instrument measures the drop in short circuit current, I_{sc} , at negligible voltage drop when the soiling specimen is placed between the cell and a light source. Additionally, it was found that our spectrophotometer could be modified to accept the specimens and measure total integrated transmission. The appended tables record the control, one month and two month outdoor exposures with percent change values obtained for each of the specimens under test (Tables 19-21).

In the Tables, the delta represents the total change in the specimen as a percentage of the measured control value. With respect to the change in short-circuit current (Table 19) , it may be observed that the lowest overall drop of power is found for Sunadex glass and that generally the best surface treatment is the coupled perfluorodecanoic acid, E-3820-103B, although L-1668 appears to work very well with the X-22417 acrylic film.

The ozone treatment, used to provide activated sites for the coupling of the L-1668 and the E-3820-103B compounds, appears to have done more harm than good. The surfaces ozone treated have much worse decay in properties than the untreated films. The SHC-1000 and the Rohm and Haas WL-81 coatings had the least benefit, the soiled values being even greater than the control values.

Values of total integrated transmission measured with a modified spectrophotometer (Table 20) , did not correlate well with the I_{sc} values. In many cases the %T trends were exactly the reverse of the short circuit current trends. This is possibly due to an inherent inaccuracy in the method of measurement.

The soiling values of these specimens will be measured every month for the period of one year and will be correlated to patterns of rain and snow.

D. Corrosion Protection

A series of corrosion tests were run with specimens primed with the new primer, (Springborn number All861). This primer is the improved composition mentioned in the previous sections and employs a tertiary amine that has greater stability to premature polymerization and the formation of color than the previous formulation. This material also has a small quantity of peroxide mixed with it to further promote adhesive bond strength. Corrosion test specimens were prepared in two ways, first as plain encapsulated metals compression molded in EVA and secondly in the form of modules encapsulated by the vacuum bag process. The metals encapsulated in modules were also duplicated in the unprimed condition. Table 22 tabulates the performance of these specimens in the ASTM B-117 salt spray chamber.

Although the new primer had noticeably improved bond strengths, the compression molded specimens did not perform quite as well as with the previous series using primer number A8921-1. In this previous series (see Table T-18, Springborn Laboratories Third Annual Report) all the metals were rated as "1", no corrosion effect. With the new primer the copper and aluminum showed no effect but the mild steel developed spots of rust and the galvanized steel became covered with a layer of white corrosion products. The corrosion resistance in module form appeared to be noticeably better than the compression molded specimens. All the specimens both primed and unprimed were rated "1", no observable effect, with the exception of the unprimed mild steel. A few rust spots were visible after the 1600 hour exposure period, and the corrosion resistance was not quite as good as the primed metal.

The module constructions on the whole survived quite well, although approximately 10% of the back surface of aluminum foil had been dissolved away. This is not surprising considering that the backside is exposed to a continual flow of concentrated salt water.

E. Hardboard Protection Experiments

Wood products (hardboards) are potentially the most cost-effective substrate materials available. To become viable candidates for this function, the deficiency of hygroscopic expansion must be overcome. Water absorption results in large dimensional changes (appx. 5×10^{-5} inches/inch/%RH) that result in warping and cell fracture as the hardboard expands. Contraction of the hardboard is not foreseen as being problematic because the cells and pottant are then placed in compression rather than tension.

A series of experiments were run to determine if the hardboard substrates could be "passivated" to humidity effects by coating the surfaces, coating the edges or a combination of the two. Additionally, the idea of equilibrating the hardboard at a high humidity prior to fabrication was briefly investigated in order to examine the contraction (cell/pottant compression) effects.

If the module is prepared with hardboard that has been equilibrated at 100% RH, then it is bound to lose moisture in the outdoor environment until it reaches the national average of 60% (providing that the coating supplied an efficient damping factor).

Initially, the effects of just coating the edges and/or the surfaces with polymer films was tried to determine the magnitude of the effect. Table 23 gives the results of this experimentation. In all cases, the measurements consisted of (a) determining the change in thickness at points centrally located on the hardboard, (b) determining the thickness change at points around the perimeter, (c) measuring the change in width, (d) measuring the change in length, and (e) measuring the change in weight. All the changes are measured as % change of the original value after equilibration at some known condition. The conditions of the initial measurements and the treatments used to passivate the hardboards are given as entries in the left column. The values in the right columns are the % change after some other exposure condition.

Some general conclusions may be drawn from the table concerning the approaches explored to date. In general, none of the techniques to isolate or passivate the hardboards from the exposure to variations in RH or processing conditions are successful. Neither coating the surfaces of the hardboard with Korad acrylic film or coating the edges with epoxy cement appears to slow the moisture loss/absorption effects to any significant degree, nor does a combination of the two. Upon passing the control and treated hardboards through the vacuum bag fabrication cycle, the specimens lost dimensions, weight and moisture in proportion to the RH to which they had been initially equilibrated. Coating and sealing techniques appeared to have no effect in retarding this change.

Studies of this nature were continued, but with the use of more sophisticated coatings. Tedlar and aluminum foils were used in combination with EVA and EMA pottants performing as hot melt adhesives to bond them to the wood surface.

The conditions of the initial measurements and the treatments used to passivate the hardboards are given as entries in the left column. The values in the right columns are the % change after some other exposure condition. Due to the difficulty and inaccuracy in measuring the physical dimensions of the modules, only weight was used as the measure of change.

In all cases the coating treatments were ineffective in preventing loss of significant amounts of water (weight loss) from the hardboards and therefore the prevention of dimensional change. Even the most extreme case (13879-4) in which the hardboard was sealed first with aluminum foil, then EMA pottant as a hot melt adhesive, and then with 2 mil Tedlar, still resulted in a weight loss of 1.9% with respect to the weight of the hardboard. Repeating this experiment after equilibrating the wood at 100% RH resulted in even greater losses of moisture. Examination of these "modules" after the vacuum bag procedure showed that small holes had appeared in the aluminum foil coatings in many areas and that many bubbles had appeared in the pottant layers.

These results are not surprising if the wood is considered to be an open celled foam containing water. At 150°C the water will develop a high vapor pressure inside the hardboard and the presence of vacuum on the outside further increases the pressure differential. Passivated hardboards do not appear promising for the substrate element when used with the heat/vacuum lamination process but may be found to be suitable for the low temperature liquid casting encapsulations.

IX. UV AND THERMAL AGING AND STABILIZATION

A photovoltaic module is a device for producing useful quantities of electricity. The end-of-life for a module is when it no longer produces electricity either catastrophically or as the end point of a gradual reduction in generated electricity over time.

The encapsulation system functions to package the active electrical producing devices, the solar cells, and their electrical interconnects and other necessary electrical wiring. The purpose of encapsulation, therefore, is to provide that necessary degree of packaging in order to assure electrical generation. The primary failure modes known for the electrical system are:

1. Mechanical - breakage of solar cells, and fracture separation of interconnects.
- and
2. Corrosion - atmospheric attack of sensitive metals.

Thus encapsulation must provide the necessary degree of mechanical support and protection for the electrical hardware, and isolation of the electrical hardware from chemical and corrosive action of the environment.

In addition, the encapsulation system must assure sufficient optical transmission to the solar cells, in the response range of 0.4 to 1.1 μ m, and adequate electrical insulation to prevent against electrical shorts, arcing, dielectric breakdown, and electrical hazards to humans.

Primary, the four key, life-related requirements for the encapsulation package are:

1. Mechanical
2. Chemical
3. Optical
4. Dielectric

The encapsulation package must fulfill the demanding needs of each of these life-related requirements, both initially following manufacturing, and later during outdoor service. In turn, the weathering of the encapsulation package itself must be within bounds dictated by preserving the modules continuing ability to be a generator of electricity.

Module life, whether catastrophically terminated or subject to performance degradation, is dominantly related to the pottant, both its initial properties and its weathering behavior. This one material is vital to and involved in all four module-life concerns, optical, dielectric, chemical, and mechanical.

In addition to being low in cost, these materials must be transparent, processable, commercially available, and pliable enough not to damage solar cells from mechanical toughness or thermal expansion mismatch. In many cases, the commercially available material is not physically or chemically suitable for encapsulation use, and therefore must also be amenable to low-cost modification. Additionally, the pottant material must either have inherent weatherability, i.e., retention of transparency and mechanical integrity under weather extremes, or the potential of long life provided by cost-effective protection that can be incorporated into the material or into the module design. Pottants are regarded as being the "weak link" in the construction of solar modules and consequently receive more emphasis than the other components in terms of lifetime and reliability considerations.

The candidate pottants are all transparent polymeric materials, and in an outdoor weathering environment polymeric materials can degrade from one or more of the following weathering actions:

1. UV photo-oxidation
2. UV photolysis
3. Thermal oxidation
4. Hydrolysis.

These are chemical changes which can result in changes in optical transmission in the range of 0.4 to 1.1 μm , in the dielectric strength of the material, loss of chemical inertness, and changes in Young's Modulus and creep resistance. These pottant properties constitute a set of relevant material properties for a module life prediction methodology.

The outdoor chemical reactions which can change the relevant properties are accelerated by increases in temperature, but temperature in itself is not the degrading agent of pottants, but only the accelerator of chemical reactions which act to degrade or weather materials. A module design influences

the accessibility of a pollutant to atmospheric oxygen, water vapor, and UV, and the concentration of these co-reactants in combination with increases in temperature dictate the relative rates and directions of the various chemical reactions, and the resultant changes in relevant properties. Thus for a fixed module design, which regulates co-reactant concentrations, temperature can be considered as an index of stability, or module life potential. For a fixed module design, one or more of the pollutant relevant properties, with increasing module operating temperature, will reach a critical state, and therefore be the life-limiting mode of the module.

Increasing the temperature will increase the rate of change of the relevant property(s) toward its critical state, and thus can be defined as the "Peak Service Temperature".

Given the following;

1. knowledge from laboratory testing of which relevant property or properties of a pollutant is life-limiting
2. an experimentally measured or determined relationship illustrating the increase in rate of change of the relevant property or properties with increasing temperature
3. a definition or assignment of the critical, end-of-life value for the relevant property or properties
4. knowledge of the initial value of the relevant property or properties
5. an expression of the desired module life-time,

the "Peak Service Temperature" for a pollutant, associated with either a hermetic or non-hermetic module design, will be that temperature where the rate-of-change of the relevant property will progress the property from its initial value, to its end-of-life value over the desired module life-time.

A test plan by which these degradation effects may be observed quantified and predicted is therefore coming into strong consideration for the following work.

The evolving test program for pollutants and modules at Springborn takes shape based on the following working considerations:

1. It is assumed that increases in module operating temperature, or parts of the module (i.e., hot-spotting) leads to acceleration of mechanism which will reduce module life or durability, or additionally that there are temperature levels about which module deteriorating events begin to occur which will reduce module life or durability.
2. It is assumed that a peak service temperature can be specified for a module, which can be or will be different depending on materials of construction, design configuration (superstrate, substrate, etc.) and package engineering. The peak service temperature can be related to 20-year life, given life criteria.
3. It is assumed that the life-limiting component of a module, relative to a specification of peak temperature, is the pottant. In other words, the pottant is the thermal weak link of the chain.
4. It is assumed that the pottant peak temperature will be influenced by the module design and that the peak temperature of a pottant in a glass superstrate design with a metal foil back cover will be the maximum possible peak temperature, and higher than that for the same pottant in a substrate design with a plastic film top cover.
5. It is assumed that a properly compounded pottant incorporated into any module design whatsoever, can be developed for an assured 20-year lifetime at the nominal-operating temperature of a module which will be somewhere between 50 to 60°C. Therefore 60°C is taken as the minimum service temperature requirement, and the peak service temperature, depending on module design, will be greater than 60°C.

Item 5 leads to the first pottant developmental requirement, namely that formulation modifications intended to raise the peak service temperatures for substrate application shall not impact on the minimum service temperature requirement.

6. It is assumed that life criteria for the pottants, which will dictate the peak service temperature, must be specified in terms of module performance or durability. Consideration of module performance or durability as influenced by pottants leads initially to three dominant features which can also be experimentally monitored:

- a. decrease in light transmission in the solar cell operating range of 0.4 to 1.1 μm
- b. changes in mechanical properties, either a tendency toward embrittlement, and limited elastic character over outdoor temperature swings, or a tendency toward softness, liquid-like flow, and loss of creep resistance
- c. loss of chemical inertness with the encapsulated components of the electrical circuitry or components, for example copper, solder, terminal plates, etc.

It is anticipated that one of these for each pottant will dictate the peak service temperature, via rate of change to an allowed amount specified for 20-year life. Accepting that the peak service temperature is to be dictated by the criteria set forth for the pottants, then package engineering, and all other materials of construction must meet this temperature requirement.

7. It is assumed that UV stabilizers may possibly be lost by physical means (migration, volatility, etc.), and that state of the art anti-oxidants are consumed by oxygen (mechanism of protection) and also susceptible to physical loss. Thus the closed or isolated module design, glass superstrate with metal foil backcover, prevents oxygen influx, physical loss of additives, and venting of pottant breakdown products, and therefore as indicated earlier, is anticipated to define for each pottant the maximum peak service temperature. An exception may be that unvented

pottant breakdown products may be chemically reactive toward encapsulation electrical hardware, thus causing the maximum peak service temperature to be dictated by this behavior. On the other hand, the open module designs such as substrate modules with plastic film top covers, and glass superstrate designs with other than metal foil back covers, are anticipated to have lower peak service temperatures due to oxygen influx and product venting. Alternatively, chemical activity with electrical hardware may be the pacing item.

Test Plan

A multi-stage, consecutive event test plan is proposed:

1. Fully compounded and cured industrial ready pottant specimens, with at least embedded copper and possibly other metals will be thermally aged at 80, 105, and 130°C under closed conditions (isolated from oxygen and water vapor, and unventable) to determine maximum peak service temperature for each pottant.
2. Fully compounded and cured industrial ready pottant specimens, with at least embedded copper and possibly other metals will be thermally aged exposed in open, air-circulated ovens at 60, 80, 105, and 130°C. This test will assess the mandatory requirement of life at 60°C, and determine the peak service temperature for open module designs.
3. If maximum peak service temperature is dictated by the pottant, this will be considered the limit, and no further work to raise the limit will be expended. If, however, maximum peak service temperature is dictated by chemical activity of compounding additives, then effort will be expended to identify improved compounding additives to raise the maximum peak service temperature to that limited by the pottant. As a corollary therefore, cured only pottant specimens without all of the other compounding additives will be included in test No. 1 (closed conditions).

4. If peak service temperature determined for the open aging test (2) is equal to or slightly less than the maximum peak service temperature, no further efforts at pottant improvements will be carried out. As this is not anticipated, efforts are envisioned to improve on (raise) the peak service temperature by adjustments in compounding chemistry, consistent with the mandatory requirement of life at 60°C.
5. Tests 1 through 4 will be carried out with pottant materials, but in parallel, closed (glass superstrate/metal foil) and open (substrate/plastic film top cover) modules with metal strips will be fabricated and thermally exposed at 60, 80, 105, and 130°C. This test will also assess effects of fabrication, if any.

With respect to efforts intended to raise the peak service temperature for open designed modules, particularly with anti-oxidants, it is recognized that there are two versions for these materials, designated as high temperature anti-oxidants and low-temperature anti-oxidants. The temperature break-point for efficient use of these versions is somewhere between 110 and 150°C. If maximum peak service temperature (closed design) is below 110°C, compounding improvements related to raising the open peak service temperature can be limited to low-temperature anti-oxidants.

If, however, maximum peak service temperature is greater than 110°C, then compounding efforts to raise the open peak service temperature may involve anti-oxidant mixtures, one for life at 60°C, and another for high temperature performance. Large area open module designs operating at 60°C will need the protection of the low-temperature anti-oxidant, whereas portions of the pottant adjacent to hot solar cells will need the protection offered by the high-temperature anti-oxidant.

The optical measurements program to be carried out at Springborn of oven-aged pottant specimens will include broad wavelength-dependent measurements encompassing the UV, visible, and IR range. From this, a total integrated light transmission value will be determined for the pottant, and then a total integrated light transmission value for the solar cell operating range

of 0.4 to 1.1 μm will also be generated. Additionally, the short-circuit current of a standard solar cell positioned behind the aged specimen will also be measured.

Modules exposed to oven aging at 60, 80, 105, and 130°C will not be destructively analysed but rather, the following non-destructive approach is being considered. The modules will be visually examined, condition of the metal noted, and IV traces measured with a standardized light source. The modules with discrete wave-length bands and measurement of short-circuit current, I_{SC} , associated with each wavelength band. Possibly electrical output patterns will be monitored depending on usefulness identified in on-going work at Rockwell and Colorado State University.

Modules will be fabricated and exposed outdoors at Enfield, Connecticut, and possibly at Woburn, Massachusetts, DSET, and in Florida.

Springborn will fabricate test modules of various designs with the candidate pottants, and measure the back-bias voltage behavior in the dark (Clemson test). This short-time test is anticipated to rank pottants and designs in the same order as the longer term oven aging test, and may emerge as a valuable test concept to be included as a qualifying test method for "Specifications and Requirements" of pottant materials.

Anticipating that peak service temperatures determined by oven aging may be lowered when materials or modules are simultaneously exposed to UV light, guidance for selecting test temperatures in the JPL test chambers, and RS/4 sunlamps derive from the oven tests. It is assumed that UV exposure will not be instrumental in raising peak service temperatures above those determined by oven aging. Detailed plans for indoor UV testing will be worked out later.

Test Methods for "Specifications and Requirements"

A document describing "Specifications and Requirements" will eventually be prepared for each construction element of a module, and already some of these items are evolving from practical experiences. A list of these items as currently generated are shown for various construction elements in the table in the Introduction. Many of these "Specifications and Requirements" will require a test method for measurement. A major task for Springborn will be generation of appropriate and relevant test methods.

Material Test Plan Summary

Pottant relevant properties:

- . Optical Transmission - 0.4 to 1.1 um
- . Dielectric Properties - design thickness capable to withstanding 3000 VDC
- . Chemical Inertness - toward electrical hardware
- . Mechanical Properties - 1) Young's Modulus
2) Creep Resistance

Design options:

. Hermetic Designs

Example:

Glass superstrate with
atmospheric barrier back-
covers (i.e., metal foils)

1. Isolation of organic material interlayers from exposure to atmospheric oxygen and water vapor.
2. Prevention of venting of volatiles, chemical reaction products from organic interlayers.

. Non-Hermatic Designs

Examples:

- a) glass superstrate with plastic film back covers.
- b) substrate modules with plastic film front covers.

1. Permeation access of organic interlayers to atmospheric oxygen and water vapor.
2. Permeation venting from organic interlayers.

Exposure Conditions:

- . Oven aging, open and closed systems, 60, 80, 105, 130°C
- . Fixed angle, Enfield, Connecticut; Phoenix, Arizona; and Florida
- . Continued RS/4 exposures
- . Outdoor photothermal aging at 70, 90, and 105°C

X. CONCLUSIONS

1. A survey was made of elastomers that could have potential as gasket materials for use as the supporting edge and carrier of the photovoltaic module. The most critical properties are the need for low compression set and low cost. Of the four elastomers of interest - EPDM, Neoprene, EVA, and silicone - EPDM elastomers are the most cost effective. EPDM is the principal elastomer used for automotive weather-stripping. A survey was first conducted into the sources of EPDM elastomers and companies with the capability of supplying finished goods. Nine companies were identified who supply gaskets specifically for the solar industry.

2. A study was also made of the commercial availability of sealants. Sealants are required to seal the edge of the photovoltaic module between the module edge and the rubber gasket surrounding it. Non-curing sealants are believed to be a better choice due to their ability to impart a self-healing characteristic. Major manufacturers were identified and contacted for products having the desired properties. Two general types of sealants offer the highest potential: tapes and low solvent gunnable systems. Butyl sealants to have the most desirable cost/performance characteristics. Four major types of sealants are available in the market - hot melts, hardening and non-hardening, tapes and caulks. Since it is not yet possible to identify a final compound that optimizes cost/performance, this survey is continuing.

3. The butyl acrylate syrup system developed during this period of time appears to be well suited to the needs of the industrial fabricator. The long pot life and rapid cure time at low temperatures and insensitivity to moisture all lead to a very usable liquid casting system. Actual field performance will be assessed as soon as sufficient quantities of this pottant become available to ship to solar module manufacturers. Although expected to be excellent, the outdoor weathering performance of this material is not known, however. Specimens of a prototype formulation have been exposed to almost 3,000 hours of RS/4 ultraviolet radiation with no decay in properties.

The formulation, as it stands now, is in the stage ready for industrial evaluation. The properties may be changed in the future to yield a "technically ready" pottant that represents the best possible combination of properties that the chemistry will permit and will be based on the recommendations of industrial users.

4. The EMA pottant film is similarly in the stage of readiness for industrial evaluation and the properties may also be modified at a later date in response to industrial requirements. The current EMA formulation does not appear to present any difficulties in terms of lamination and module processing. No broken cells have been noticed in any module prepared with this pottant. The current disadvantage with this pottant is that long cure times are required to develop high gel contents. However, experiments in thermal creep have not demonstrated the necessity for any gel content at all. Possibly this resin may not have to be cured in order to be a useful encapsulation compound. Samples are being provided for industrial evaluation at this time.

5. Differential thermal analysis has given encouraging results concerning the temperature at which the onset of degradation takes place in some of the pottant materials of interest. A difficulty is presented, however, in that it is not directly possible to correlate the results of this evaluation to the accumulated heat history experienced by the pottant during years of outdoor aging at the module operating temperature. Further tests on thermal stability need to be performed that more closely simulate the conditions that may be found in a module at the upper expected limit of its operating temperature in order to verify the absence of degradation occurring at lower temperatures. DTA will be used in future work for the selection of antioxidants to optimize the protection that can be given to the resin. Operating in the isothermal mode, DTA is useful for determinations of antioxidant efficiency and will permit selection of the most appropriate compounds.

6. The new primer, designated All861-1 (Springborn Laboratories' number) is the most efficient primer formulated to date for promoting the adhesion of the curable EVA composition to glass and mild steel. The highest bond strengths obtained to date have been found with this system. Other primers will have to be investigated for use with copper and aluminum, should these materials be used in modules in the future.

7. The aliphatic polyurethane casting syrup, Z-2211 from Development Associates, Inc. appears to be a good prototype formula for industrial fabrication trials. The system features exceptional clarity, absence of color, very low mixed viscosity, rigid gel and cure time, and built-in stabilizer package. Custom formulations with modified properties may also be ordered. Additionally,

related formulations have a history of outdoor use as bottle coatings and automotive rub strips.

8. Only two months of results are available in the soil resistant coating study, however some observations of materials performance can be made. The surface with inherently the best soil resistant characteristic is glass (Sunadex). Of the treatments, the fluorosilane form 3M designated L-1668 appears to have the best properties. Measurements of the efficiency of these treatments will continue on a monthly basis for twelve months with a correlation of weather patterns (rainfall).

APPENDIX

TABLE 1

**GEL CONTENT DETERMINATION
(EVA)**

The degree of cure of the resin may be determined in a simple laboratory procedure as follows:

1. Remove a small piece of cured resin of 1 to 2 grams weight and weigh on an analytical balance to three places.
2. Place the specimen in 100 ml of toluene and heat to 60°C for a minimum of four hours.
3. Pour the mixture through a piece of weighed filter paper to catch the gel fraction and permit to drain completely. "Whatman" number 54 paper is adequate.
4. Dry the filter paper and gel fraction at 60°C for three to four hours. (No odor of toluene solvent should remain.)
5. Weigh to three places and subtract the weight of the filter paper.
6. The gel content is calculated simply as:

$$\% \text{ Gel} = \frac{\text{weight of polymer residue from toluene}}{\text{weight of original specimen}} \times 100$$

7. Gel contents in excess of 65% may be regarded as acceptable cured. Springborn Laboratories shows gel contents consistently in the range of 75% to 80% resulting from the described lamination process.

TABLE 2

FORMULATION OF PRIMER DEVELOPED BY DOW CORNING CORPORATION
FOR ETHYLENE VINYL ACETATE POTTANT

<u>Component</u>	<u>Composition</u>
Dow Corning Z-6030	90 parts by weight
Benzyl dimethyl amine	10 parts by weight
Lupersol 101 peroxide	1 part by weight

For use: dilute the above mixture to 5% active in methanol solvent. Anhydrous, or dry methyl alcohol is desirable for this preparation. This mixture may be used as a dip, spray or brushed onto the surfaces to be primed. Due to its action as a chemical coupling agent, not an adhesive, thin layers are much more effective than thick coatings and a single application from a dilute solution results in high strength and high reliability bonds when used with the EVA encapsulant copolymer.

After application of this primer, the required open time is very short and lamination may commence as soon as the solvent has evaporated from the surface (appx. 15 minutes). Surfaces so primed have been found to be active for at least one day after application.

- NOTES:
1. Adequacy of bonding EVA pottant to fluorocarbon films (e.g., Tedlar) with this primer system not yet demonstrated.
 2. Diluted primer mixture in methanol available from Springborn under the designation "A-11861-1, EVA Primer".

TABLE 3
LONG TERM THERMAL AGING
Circulating Air Oven
EVA A9918

Time (a)	Property	70°C	90°C	130°C
1 Week (168 hours)	Tensile (psi)	2685	2200	2000
	Ult. Elongation (%)	595	550	550
3 Weeks (504 hours)	Tensile (psi)	1700	1800	1240
	Ult. Elongation (%)	670	680	638
2 Months (1344 hours)	Tensile (psi)	2370	2660	1320
	Ult. Elongation (%)	600	784	647
10 Months (7200 hours)	Tensile (psi)	(a)	2120	144
	Ult. Elongation (%)		660	37
	Gel Content %	-	91.7%	88.3%
	Color	-	Clear	Brown/ Orange
	%T	-	91.7%	74%
	Tangent Modulus (psi)	-	833	335

Control	Tensile (psi)	2160
(Unaged)	Ult. Elongation (%)	677

(a) Specimens Lost.

C-2

TABLE 4

EMA EXTRUSION RUN: SUMMARY

Formulation: No. A13439

Preparation: Blend 50 lb quantities in a 55 gallon drum by tumbling. Mix time minimum, 30 minutes. Product (hopper feed) is wet translucent pellets.

Formulation: EMA Base resin TD-938	50 Lbs	100 Parts
Lupersol 101	340 Gms	1.5 Parts
Cyasorb UV-531	68.1 Gms	0.3 Parts
Naugard-P	45.4 Gms	0.2 Parts
Tinuvin 770	22.7 Gms	0.1 Parts

Extruder: Hartig, 2 1/2 inch barrel

Screw: Two stage compounding screw, 3.5:1 compression, 24:1 L/D

Screw Speed: Approximately 32 rpm

Die: Full width, 33"; set gauge, 0.020"

Barrel and Die

Temperatures:

Zone:	1	2	3	4	5	3	9	10	11
Set:	195	195	195	195	195	185	185	185	185
Run:	200	205	220	220	200	210	200	200	195
(°C)	93°	96°	104°	104°	93°	99°	93°	93°	90°

Barrel	Adaptor	Die
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Screen Pack: 20-100-80-20 mesh screens

Back Pressure: 3,000-3,200 psi

Blowers for Cooling: zones 2, 3, 4 on

Take up Rolls #2, 74°F, #3 and #4, 54°F

Take up Speed: approx. 4.2'/minute, appx. 250' linear/hour

Throughput: approx. 70-80 lbs/hour

TABLE 5

Preparation of Butyl Acrylate Syrup

Laboratory Procedure

1. Distill the butyl acrylate monomer to insure purity
2. Polymerize as a 50% w/w solution in reagent grade cyclohexane at 80° C for 16 hours under a nitrogen atmosphere. The polymerization is initiated by 0.01% (weight on the monomer) of AIBN azo catalyst.
3. The resulting polymer/solvent reaction mixture is then devolatilized using a rotary vacuum evaporator operating at 60°C and approximately 28 in. Hg pressure. This stage is slow, requiring at least 8 hours to yield solvent free polymer. The yield of polymer is quantitative and it remains in the flask as a crystal clear tacky resin of an estimated molecular weight of 400,000 (\bar{M}_w - GPC)^(a).
4. More liquid monomer is then added to the flask to dissolve the polymer and yield a 100% active acrylic based casting syrup. The remaining polymer cannot be removed from the flask due to its extremely high viscosity, consequently the final solution is prepared in situ by adding monomer to the flask and dissolving the polymer out as a 33% solution.
5. The resulting solution is then precatalyzed by adding a small amount of initiator so that polymerization and cure will result on heating. The syrup so prepared is a transparent fluid of 10,000 centipoise viscosity which may be used directly as the solar module pottant.

(a) Molecular weight determined by gel permeation chromatography.

TABLE 6

Cure Experiments; Butyl Acrylate System

Run No.	Initiator ^(a)	Temperature, C ^(b)	% Gel
1	V-64	60	1.01
2	V-52	60	5.38
3	V33W	60	9.05
4	BPO	60	19.05
5	L-101	60	NP
6	V-64	75	3.85
7	V-52	75	2.56
8	V-33W	75	3.24
9	BPO	75	19.08
10	L-101	75	NP
11	V-64	85	2.08
12	V-52	85	3.55
13	V-33W	85	8.05
14	BPO	85	12.17
15	L-101	85	2.98

Code: (a) 0.5% by weight on mixture
(b) One hour at this temperature
NP No polymerization occurred
V-64 Vazo 64; Azobisisobutyronitrile
V-52 Vazo 52; 2,2'-Azobis (2,4-dimethylvaleronitrile)
V-33W Vazo 33W; 2,2'-Azobis (2,4-dimethyl-4-methoxyvaleronitrile)
BPO Benzoyl peroxide
L-101 Lupersol 101; 2,5-dimethyl-2,5-di(t-butylperoxy) hexane

TABLE 7

Crosslinking Agent Selection

Formulation: ^(a) 60% butyl acrylate monomer 35% poly-butyl acrylate solids 5% crosslink agent		
Crosslinking Agent ^(b)	Swell Index	Cured Gel Content ^(c)
SR-230 (diethylene glycol diacrylate)	380%	63%
SR-268 (tetraethylene glycol diacrylate)	360%	59%
SR-238 (1,6-hexanediol diacrylate)	380%	68%
SR-209 (tetra ethylene glycol dimethacrylate)	340%	50%
SR-239 (1,6-hexanediol dimethacrylate)	280%	48%
SR-297 (1,3-butylene glycol dimethacrylate)	370%	46%
SR-210 (polyethylene glycol dimethacrylate)	330%	48%
SR-205 (triethylene glycol dimethacrylate)	300%	43%

(a) All swell/gel specimens were cured under nitrogen for one hour at 60°C and were initiated with 0.5 phr of AIBN.

(b) "SR" number designation is from the Sartomer Corporation.

(c) Gel content determined from weight loss after extraction with toluene at 60°C.

TABLE 8

Butyl Acrylate Pottant: Initiator Studies
(Based on Standard Syrup Formulation Number A12805)

Initiator <u>0.5%</u>	Promoter <u>0.1%</u>	<u>Time to Cure (minutes)</u>			
		<u>20°C</u>	<u>35°C</u>	<u>45°C</u>	<u>55°C</u>
Lupersol-225	None	NP	NP	NP	NP
Lupersol-225/ Benzoyl Peroxide	None	NP	NP	NP	NP
Lupersol-225/ Lupersol-11	None	NP	NP	32	21
<hr/>					
Benzoyl Peroxide	None	NP	NP	NP	47
Benzoyl Peroxide	Cobalt Naphthenate	NP	NP	NP	27
Benzoyl Peroxide	Stannous Octoate	NP	70	34	12
Benzoyl Peroxide	Zinc Octoate	NP	NP	NP	19
<hr/>					
Vazo - 33W	None	39	5.5	4	3
Vazo - 33W	Cobalt Naphthenate	58	-	-	-
Vazo - 33W	Stannous Octoate	30	4	3.5	2.5
Vazo - 33W	Dibutyl Tin Dilaurate	37	-	-	-
Vazo - 33W	Zinc Octoate	38	-	-	-
<hr/>					
Lupersol-11	None	NP	NP	21	12
Lupersol-11	Cobalt Naphthenate	NP	NP	5	2
Lupersol-11	Stannous Octoate	NP	29	11	5.5
Lupersol-11	Dibutyl Tin Dilaurate	NP	NP	18	7.5
Lupersol-11	Zinc Octoate	38	-	-	-

TABLE 9Butyl Acrylate - Final FormulationsButyl Acrylate Syrup With 0.5% Alperox-F

<u>Formulation Number</u>	<u>Additives</u>	<u>Room Temperature</u>	<u>50°C</u>	<u>60°C</u>	
<u>Al3446-</u>					
1	Tinuvin-P, 0.5%	NP	-	20	
2	Tinuvin-P, 0.5% Promoter, 0.1%	NP	26	9	
3	5-Vinyl Tinuvin, 0.5%	NP	-	18	
4	5-Vinyl Tinuvin, 0.5% Promoter, 0.1%	NP	48	16	
5	Tinuvin-P 0.5% Tinuvin 770, 0.1%	NP	-	27	
6	Tinuvin-P, 0.5% Tinuvin 770, 0.1% Promoter, 0.1%	NP	26	11	
7	5-Vinyl Tinuvin, 0.5% Tinuvin 770, 0.1%	NP	-	25	
8	5-Vinyl Tinuvin, 0.5% Tinuvin 770, 0.1% Promoter, 0.1%	NP	60	14	
9	Tinuvin-P, 0.25% Tinuvin 770, 0.1%	NP	Over 60	24	
10	Tinuvin-P, 0.25% Tinuvin 770, 0.1% Promoter, 0.1%	NP	40	15	
11	Tinuvin-P, 0.25% Tinuvin 770, 0.05%	NP	Over 60	18	<u>70°C</u> 14
12	Tinuvin-P, 0.25% Tinuvin 770, 0.05% Promoter 0.1%	NP	42	15	11

NP = No polymerization noticed within an eight hour period of time.

TABLE 10

ELASTOMERS FOR SOLAR MODULES

CLASS PS ELASTOMER SCREENING TESTS

<u>Class PS Material</u>	<u>Hardness¹ Grade</u>	<u>Ultimate Elongation</u>	<u>Compr. Set 70 h, 150°C²</u>	<u>Compr. Set 166 h, 10°C</u>	<u>Hardness Change²</u>	<u>Ultimate Elongation Change²</u>	<u>Tensile Strength Change²</u>	<u>Volatiles Lost²</u>
<u>Silicone</u>								
SK-7330	5	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺
Silastic 747	7	P	P ⁺	P ⁺	P ⁺	P	F	F
ES-70	7	P ⁺	P	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺
<u>EPDM</u>								
E-633	7	P ⁺	F ⁻	F ⁻	P	F ⁻	F	F ⁻
78E-09-28-2	6	P ⁺	F ⁻	F ⁻	F ⁻	F ⁻	P ⁺	F
Nordel 3300-11	8	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺	P ⁺	F
<u>Fluorocarbon</u>								
Viton 31323-0731	8	P ⁺	P ⁺	F ⁻	P ⁺	P ⁺	P ⁺	P ⁺
Viton PLV 1008	8	P ⁺	P ⁺	F ⁻	P ⁺	P ⁺	P ⁺	P ⁺
<u>Epichlorohydrin</u>								
HM 14-10-1	6	P ⁺	F ⁻	P ⁺	P	P	P	F ⁻
HM 13-SECJ-2	7	P ⁺	F	P ⁺	P	P	P ⁺	F
HM 13-27-1	8	P ⁺	F	P ⁺	F	F	P	F ⁻
<u>Ethylene Acrylic</u>								
Vamac 3300-12	7	P ⁺	F	F ⁻	P ⁺	F	P ⁺	F ⁻
<u>Chlorosulfonated Polyethylene</u>								
Hypalon 3300-10	7-8	P ⁺	F ⁻	F ⁻	P ⁺	P	P ⁺	P ⁺
<u>Polyacrylic</u>								
210-108-35-1	6-7	F	P ⁺	P	P ⁺	P ⁺	P ⁺	P ⁺
<u>Bromobutyl</u>								
SEX-122	6	P	F	F	P ⁺	F	P	F ⁻
<u>Butyl</u>								
SEX-123	5-6	P ⁺	P ⁺	F ⁻	P ⁺	P ⁺	P ⁺	F ⁻
SR 35020	5	P ⁺	F ⁻	P ⁺	P ⁺	P	F ⁻	F ⁻

¹(Hardness grade x 10) ± 5 = Shore A durometer hardness

²Materials exposed to 150°C/70 h

P = pass by relatively small margin

P⁺ = pass by substantial margin

F = fail by relatively small margin

F⁻ = fail by substantial margin

Source : M. A. Mendelsohn, et al., Collector Sealants and Breathing, Report number ALO-15362-1, by Westinghouse Electric Corporation, Pittsburgh, Pa., Feb. 20, 1980. Work performed under contract no. DE-ACO4 -78CS15362

TABLE 11

TYPICAL ELASTOMER FORMULATIONS AND COST

Raw Material Costs

Resin Gum Stocks:	\$ /lb
Neoprene WRT	1.23
Vynathane EY-904-25	1.04
Epsyn 5508	0.8625
Epsyn N557	0.7080
Silastic GP437	2.37
Fillers:	
Carbon Black (typical)	0.50
Clay (typical)	0.50
Cabosil MS-7	2.77
Process oil	0.50

Formulations (representative)

1. Neoprene -weather resistant Cost: \$0.87/lb.

Neoprene WRT	100
Carbon Black	55
Clay	20
2. EPDM-Weatherstripping compound (\$0.58/lb)

Epsyn 5508	70
Epsyn N557	45
Carbon Black	200
Process Oil	130
3. EVA (\$0.85/lb)

Vynathene EY904-25	100
Carbon Black	55
4. Silicone (\$2.53/lb)

Silastic GP-437	100
Cabosil MS-7	65

Solar Module Gaskets - Product Specification Typical Manufacturer's Literature

ELASTOMER (POLYMER) SELECTION

Experience has shown that most solar collector sealing applications are best handled with an elastomer of either an EPDM or silicone base.

PAWLING E633 EPDM

Pawling Rubber has developed a high strength EPDM elastomeric material specifically compounded to meet the physical requirements of collector sealing (glazing) where the temperature *at the seal* will be 250°F or less. A majority of the collectors in use today can be adequately glazed with our E633 EPDM, for although the highest anticipated stagnate temperature at the collector plate surface may exceed 300°F, the temperature at the seal will be lower. Collectors sealed (glazed) with gaskets made by Pawling from our E633 EPDM have passed the HUD thirty day stagnation tests.

PAWLING 96-B-24 SILICONE / PAWLING 80623 SILICONE

Pawling Rubber has developed this special silicone elastomeric material for use in solar applications where the temperature *at the component* will continually exceed 300°F. This may be the case with spacers or thermal breaks in contact with or in very close proximity to the collector plate, or on some inner seals in double glazed units. Collectors sealed (glazed) with gaskets made by Pawling from our 96-B-24 and 80623 Silicone have passed the HUD thirty day stagnation tests.

The physical characteristics and specifications applying to Pawling E633 EPDM and Pawling 96-B-24 and 80623 Silicone are listed below so that you may have more exacting descriptions of the materials to compare the strengths and limitations of each.

COMPARATIVE DATA

	Pawling E633 EPDM	Pawling 80623 Silicone Pawling 96-B-24 Silicone	
Resistance To:	Ethylene Propylene Polymer	Polysiloxane Polymer	* These temperature ranges are recommended limits for normal service life. Occasional or intermittent temperature exposure above these limits may cause slight accelerated heat aging which results in some hardening and loss of flexibility of that portion of the part exposed to the high temperature. However, the seal will not cease functioning.
Water Absorption	Excellent	Excellent	
Oxidation	Excellent	Excellent	
Ozone	Outstanding	Outstanding	
Sunlight Aging (Ultra Violet)	Outstanding	Excellent	
Heat Aging	Excellent	Outstanding	
Low Temperature	Excellent	Outstanding	
Temperature Range	-60°F to +300°F*	-60°F to +500°F*	
Rebound Hot	Excellent	Excellent	
Rebound Cold	Excellent	Excellent	

Volatilization (outgassing) - Used as recommended, outgassing of E633 EPDM, 96-B-24 and 80623 silicone is *infinitesimal*. No measurable light transmission degradation has been noted in the field or laboratory.

96-B-24 and 80623 SILICONE			E633 EPDM		
Specification ASTM D2000 5GE608			Specification ASTM D2000 3BA 620 A ₁₄ B ₁₃ C ₁₂ F ₁₇ Z ₁ Z ₂ Z ₃ Z ₄ Z ₅		
A ₁₉ B ₃₇ C ₁₂ E _{A14} E _{O16} F ₁₁₀ P _{Z1} Z ₂ Z ₃ Z ₄			Original Properties:		
Original Properties:	As Specified	As Obtained	Durometer (Shore A)	As Specified	As Obtained
Durometer (Shore A)	60 ± 5	60	Tensile Strength	60 ± 5	60
Tensile Strength	Min. 700 psi	900 psi	Elongation	Min. 2000 psi	2200 psi
Elongation	Min. 200%	225%	Tear Resistance (G ₂₁)	Min. 400%	425%
Oven Aged 70 Hrs @ 437°F (A ₁₉)					200
Durometer Change	Max. +10	+4	Oven Aged 70 Hrs @ 112°F (A ₁₄)		
Tensile Change	Max. -25%	+3%	Durometer Change	Max. +10	+5
Elongation Change	Max. -20%	-7%	Tensile Change	Max. -25%	-4%
Compression Set 22 Hrs @ 347°F (B ₃₇)			Elongation Change	Max. -25%	-10%
% Deflection	Max. 25%	20%	Compression Set 22 Hrs @ 158°F (B ₁₃)		
Water Immersion 70 Hrs @ 212°F (E _{A14})			% Deflection	Max. 25%	20%
Volume Change	± 5%	+0.5%	Water Immersion 70 Hrs @ 212°F (E _{A14})		
Ozone Resistance 168 Hrs @ 50 PPHM +104°F @ 20% Strain (C ₁₂)			Volume Change	+10%	+0.5%
No Cracking or Checking - Passed			Ozone Resistance 168 Hrs @ 50 PPHM + 104°F @ 20% Strain (C ₁₂)		
Cold Test, Flexibility Brittle Point @ -85°F (F ₁₁₀)			No Cracking or Checking - Passed		
No cracking before or after impact - Passed			Cold Test, Flexibility Brittle Point @ -40°F (F ₁₇)		
Staining Test: Non-staining as per ASTM D 925, method B - Non-staining (P)			No cracking before or after impact - Passed		
Special Tests: Samples baked 14 days @ 350°F in a tightly covered 500 ml Berzelius Beaker on a hot plate			Special Tests: Samples baked 7 days @ 250°F in a tightly covered 500 ml. Berzelius Beaker on a hot plate (Z ₁ - Z ₄)		
Z ₁ - Maximum weight loss 0.04%			Z ₁ - No oily emissions, fogging or crystalline formations within the beaker or on the glass cover plate.		
Z ₂ - No appreciable fogging of glass cover plate or beaker sides.			Z ₂ - Maximum weight loss 1.0%		
Z ₃ - Maximum +5 durometer change (Shore A)			Z ₃ - Maximum +5 durometer change (Shore A)		
Z ₄ - No cracking when flexed 180° several times.			Z ₄ - No cracking when flexed 180° several times		
			Special Test: Tear resistance. (Z ₅)		
			Z ₅ - Tear resistance (ASTM D 624, Die C) minimum 200 p.s.i.		

Inasmuch as Pawling Rubber Corporation has no control over the use to which others may put the material, it does not guarantee that the same results as those described herein will be obtained. Each user of the material should make his own tests to determine the material's suitability for his own particular application.

Table 13

Typical Manufacturer's Literature
Solar Module Gaskets - Design Application

A TYPICAL COLLECTOR ASSEMBLY SHOWING
USES OF PAWLING ELASTOMERIC
SOLAR COMPONENTS

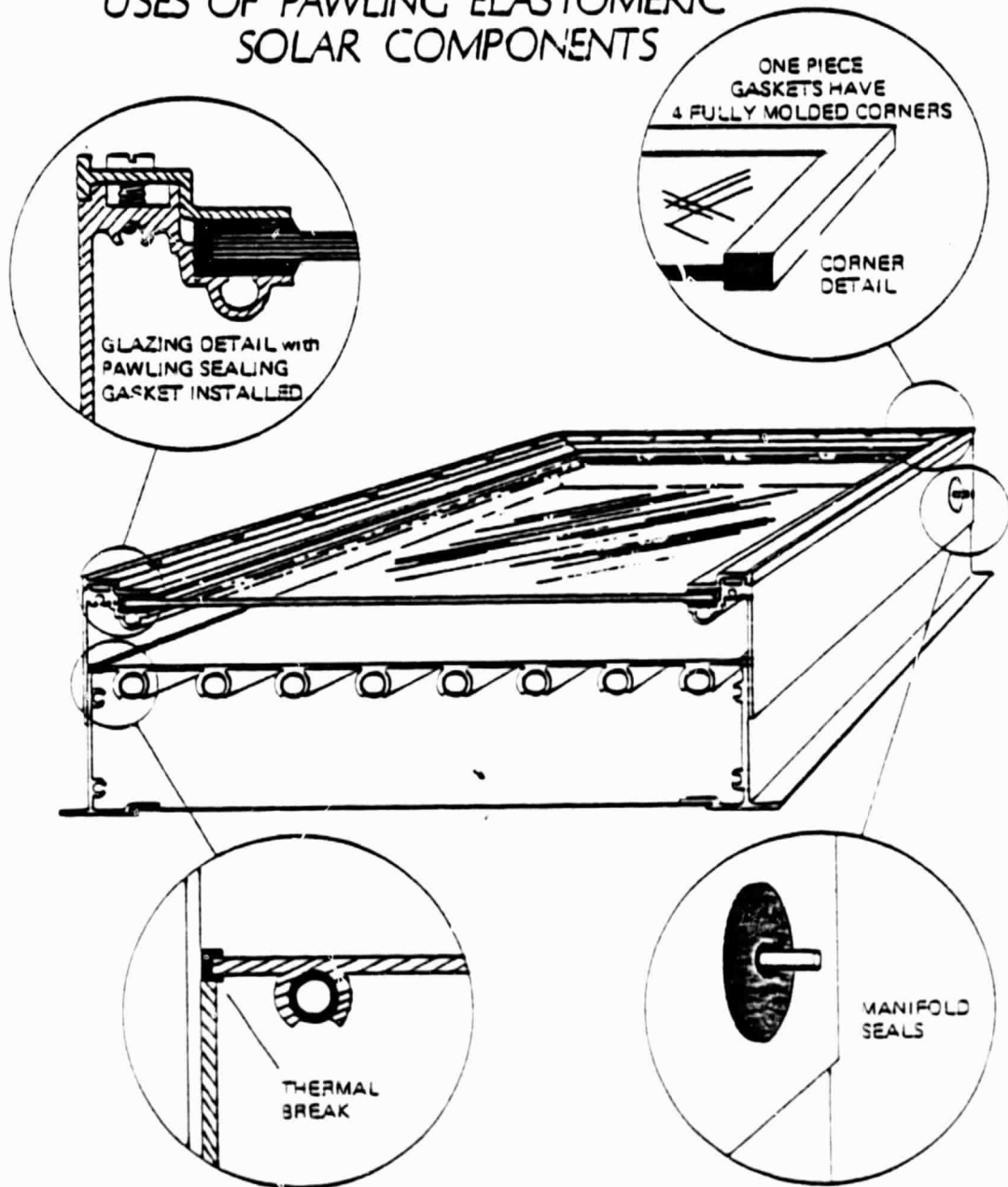


TABLE 14

Solar Gasket Materials - ASTM Specification

(page 1 of 2)

AMERICAN NATIONAL
STANDARD

ANSI/ASTM D 3667 - 78

Standard Specification for
RUBBER SEALS USED IN FLAT-PLATE SOLAR
COLLECTORS¹

This Standard is issued under the fixed designation D 3667; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last approval.

1. Scope

1.1 This specification covers the general requirements for materials used in rubber seals of flat plate solar collectors, except vertically mounted passive collectors. Particular applications may necessitate other requirements that would take precedence over these requirements when specified.

1.2 The design requirement pertains only to permissible deflections of the rubber during thermal expansion or contraction of the seal in use and the tolerances in dimensions of molded and extruded seals.

1.3 This specification does not include requirements pertaining to the fabrication or installation of the seals.

2. Applicable Documents

2.1 ASTM Standards²

D 661 Test for Indentation Hardness of Elastomeric Type Sealants by Means of a Durometer³

D 717 Definitions of Terms Relating to Building Seals⁴

D 719 Test for Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement⁵

D 395 Test for Rubber Property - Compression Set⁶

D 412 Tests for Rubber Properties in Tension⁷

D 865 Test for Rubber Deterioration by Heating in a Test Tube⁸

D 1149 Test for Rubber Deterioration - Surface Ozone Cracking in a Chamber (Flat Specimens)⁹

D 1259 Test for Rubber Property - Compression Set at Low Temperatures¹⁰

D 1349 Recommended Practice for Rub-

ber - Standard Temperatures and Atmospheres for Testing and Conditioning¹¹

D 1415 Test for Rubber Property - International Hardness¹²

D 1566 Definitions of Terms Relating to Rubber¹³

D 2127 Test for Rubber Property - Brittleness Point of Flexible Polymers and Coated Fabrics¹⁴

D 2240 Test for Rubber Property - Durometer Hardness¹⁵

D 3182 Recommended Practice for Rubber - Materials, Equipment, and Procedures for Mixing Standard Compounds and Preparing Standard Vulcanized Sheets¹⁶

D 3183 Recommended Practice for Rubber - Preparation of Pieces for Test from Other Than Standard Vulcanized Sheets¹⁷

2.2 Other Standards

RMA Handbook - Rubber Products: Molded, Extruded, Lathe Cut, and Cellular¹⁸

3. Classification

3.1 Types

3.1.1 Type C, intended for use in cold climates (below -10°C in winter)

3.1.2 Type W, intended for use in warm

¹ This specification is under the jurisdiction of ASTM Committee D 11 on Rubber and is the direct responsibility of Subcommittee D11.36 on Seals.

Current edition approved May 11, 1978. Published July 1978.

² Annual Book of ASTM Standards, Part 18.

³ Annual Book of ASTM Standards, Part 37.

⁴ Annual Book of ASTM Standards, Parts 35, 37, and 38.

⁵ Annual Book of ASTM Standards, Parts 37 and 38.

⁶ Annual Book of ASTM Standards, Parts 35 and 37.

⁷ Available from the Rubber Manufacturers Association (RMA), 444 Madison Ave., New York, N.Y. 10022.

climates (above -10°C in winter).

3.2 Grades

3.2.1 Grade designations represent differing degrees of hardness as follows:

3.2.1.1 Grade 2, hardness of 20 ± 5.

3.2.1.2 Grade 3, hardness of 30 ± 5.

3.2.1.3 Grade 4, hardness of 40 ± 5.

3.2.1.4 Grade 5, hardness of 50 ± 5.

3.2.1.5 Grade 6, hardness of 60 ± 5.

3.2.1.6 Grade 7, hardness of 70 ± 5.

3.2.1.7 Grade 8, hardness of 80 ± 5.

Note 1 - The grade to be used in a particular application depends on the design of the seal and must be specified by the designer.

3.3 Classes

3.3.1 Seals shall be classified as follows:

3.3.1.1 Class PS, preformed rubber seal.

3.3.1.2 Class SC, sealing compound.

Note 2 - Class SC material shall not be used in designs where the seal is under mechanical stress.

4. Definitions

4.1 Refer to the definitions of terms in Definitions C 717 and D 1566.

5. Materials

5.1 Seals shall be made from rubber compounds that are impermeable to ultraviolet light and when vulcanized, conform to the requirements in Section 6.

6. Requirements

6.1 Class PS material shall conform to the requirements given in Table 1.

6.2 Class SC material shall conform to the requirements given in Table 2.

7. Dimensions

7.1 The design of the seal shall not permit the rubber to deflect more than 25 % in any direction during thermal expansion and contraction of the solar collector.

Note 3 - If the thermal coefficient of linear expansion for the rubber is not known, a value of 0.0001/K may be assumed for design purposes.

7.2 The tolerances in dimensions shall conform to the following designations in the RMA Handbook.

7.2.1 Molded Seals

7.2.1.1 Commercial Dimensions - RMA A3-F3-T 032

7.2.1.2 Critical Dimensions - RMA A2-F3-T 032

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7.2.2 Extruded Seals

7.2.2.1 Commercial Dimensions - RMA A2-F3.

8. Workmanship

8.1 Class PS seals shall be free of blisters, checks, cracks, and other imperfections that can affect their ability to make or maintain a water-tight seal.

8.2 Class SC material shall be uniform in composition and be free of defects that may affect serviceability.

9. Test Methods

9.1 Class PS Material - Prepare the specimens as prescribed in Recommended Practice D 3183 and test the material in accordance with the test methods given in Table 1. For control of production, specimens may be taken from standard test sheets prepared in accordance with Recommended Practice D 3182, using the same unvulcanized material used to prepare the seals and vulcanizing the material at the same temperature used for the seals to an equivalent state of vulcanization.

9.2 Class SC Material - Prepare five sheets approximately 150 by 150 by 2 mm in accordance with instructions supplied with the sealing material. Also, prepare five adhesion specimens in accordance with Method C 719. Preferably, prepare each sheet and adhesion specimen from material in a different container. Condition the sheets and adhesion specimens for 14 days at a temperature of 23°C and relative humidity of 50 %. Test the material in accordance with the test methods given in Table 2.

9.3 Determine volatiles lost from the difference in masses of the specimens before and after heating for 166 h at the temperature given in Table 1 or 2 and as prescribed in Method D 865.

9.4 Determine volatiles condensable at 23°C from the difference in mass of the outlet tubes before and after heating the specimens for 166 h at the temperature given in Table 1 or 2 in accordance with Method D 865. If necessary, cool the exposed portion of the outlet tube with a stream of air to maintain a temperature of 23 ± 2°C. If any volatiles condense on the inlet tube or other parts of

TABLE 14 - Continued (Page 2 of 2)
Solar Gasket Materials - ASTM Specification

D 3667

the apparatus, add the mass of this condensed material to the mass of the material on the outlet tube.

10. Inspection and Rejection

10.1 **Class PS Material** - Manufacturers of performed seals may use their quality control systems for production inspection to assure the seals conform with this specification, provided appropriate records are kept. In case of dispute regarding the quality of a delivered product, a sample of five seals shall be taken from the lot and tested for compliance with this specification. If one of the five seals does not conform, a second sample of five seals may be taken and tested. If two or more of the ten seals do not conform, the lot may be rejected.

10.2 **Class SC Material** - Manufacturers may use their quality control systems to assure production conforms with this specification. In case of dispute regarding the quality of a delivered product, five test sheets and five adhesion specimens shall be prepared, preferably from five different packages, in accordance

with the instructions supplied with the sealing material. If one of the five sheets or adhesion specimens does not conform, an additional five sheets or adhesion specimens may be prepared and tested. If two or more of the ten sheets or adhesion specimens do not conform, the lot may be rejected.

11. Marking

11.1 The following information shall be marked either on the seal, packaging, label, or tag:

11.1.1 Name, brand, or trademark of the manufacturer;

11.1.2 Type and grade;

11.1.3 Compliance with Specification D 3667, and

11.1.4 Other information required by the manufacturer or purchaser.

12. Packaging

12.1 Material shall be protected by suitable packaging to prevent damage during shipment or storage prior to installation in the solar collector.

D 3667

TABLE 2 Requirements for Class SC Material Used to Seal Flat-Plate Solar Collectors

Property	Grade			ASTM Method
	1	2	3	
Ultimate elongation, min, %	200	150	100	D 412
Resistance to heating (for 166 h at 125°C)				D 863
Hardness change, max	10	10	10	C 661
Ultimate elongation change, max, %	30	30	30	D 412
Tensile strength change, max, %	20	20	20	D 412
Volatiles lost, max, %	1	1	1	See 10.3 ^a
Volatiles condensable, max, %	0.1	0.1	0.1	See 10.4 ^a
Resistance to ozone				D 1149
100 mPa, for 166 h at 40°C	No cracking			
Resistance to low temperature				D 2137
Type C only, max, °C	-40	-40	-40	
Adhesion loss, max, cm ²	9	9	9	C 719

^a This test is not required if the design precludes condensing of the volatiles on the cover plate(s) of the solar collector.

^b The combined loss in bond and cohesion areas for the three specimens tested shall not exceed 9 cm².

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Ritten St., Philadelphia, Pa. 19101, which will schedule a further hearing regarding your comments. Failing satisfaction there, you may appeal to the ASTM Board of Directors.

TABLE 3 Requirements for Class PS Material Used to Seal Flat-Plate Solar Collectors

Property	Grade						ASTM Method
	1	2	3	4	5	6	
Ultimate elongation, min, %	150	100	250	200	150	100	D 412
Compression set, max, %							
after 70 h at 150°C	30	30	30	30	30	30	D 395 ^a
after 166 h at -10°C	60	60	60	60	60	60	D 1279 ^a
Resistance to heating (for 166 h at 150°C) ^b							D 863
Hardness change, max	10	10	10	10	10	10	D 1415 or D 2240
Ultimate elongation change, max, %	30	30	30	30	30	30	D 412
Tensile strength change, max, %	20	20	20	20	20	20	D 412
Volatiles lost, max, %	1	1	1	1	1	1	See 10.3
Volatiles condensable, max, %	0.1	0.1	0.1	0.1	0.1	0.1	See 10.4
Resistance to ozone							D 1149
100 mPa, for 166 h at 40°C	No cracking						D 2137
Resistance to low temperature							
Type C only, max, °C	-40	-40	-40	-40	-40	-40	

^a Method B.

^b Set to be measured at 10 s after release. Lubricated plates or polytetrafluoroethylene film is recommended if the rubber adheres to the metal compression plates during test.

^c The test temperature of 150°C is used to test seals for cover plates. A seal in contact with an absorber plate should be tested at a standard test temperature listed in Recommended Practice D 1349 next above the maximum temperature of the absorber plate in service (which generally occurs under stagnation conditions and maximum radiation flux) but not less than 150°C. The higher test temperatures are: 175, 200, 225, and 250.

^d 100 mPa of ozone partial pressure is equivalent to 100 ppb at standard atmospheric pressure (100 kPa). See new terminology on ozone content expressions described in Method D 1149.

Table 15
General Survey of Sealant Compounds
and Manufacturers

Sealant	Manufacturer	Type	Form	Application	Cost/4x8 Panel Cost/Watt	Lifetime/ Weathering	Cure Time	Automation Potential
HM 1150	H.R. Fuller	Butyl- isobutylene	Slugs	Hot melt extrusion	0.24 0.000857			Excellent
HM1081A	"	Hot Melt Butyl	Rope or 55/gal drum	"	\$.19 \$.00068	Excellent	10-20 secs.	Excellent
Durifibbon 72-6417	National Adhesives	Hot Melt Butyl	55/gal	Hot Melt Extrusion	.20 .00070	Excellent	60 sec.	Good
4050	"	Butyl Sealant	Tape or 55/gal drum	Pressure Flow Gun	.20 .00078	Good	Tack Free 3 hrs Cure-3 days	Poor
5354	3M	Butyl Tape	50' Roll 3/8"x1/8"	-	1.32 .00471	Excellent 20 yrs	Non-Hardening	Poor
404	3M	Synthetic elastomer	55 gal drum	Pressure flow gun	0.14 0.00050	Good	Tack free 2 hrs cure-3days	Poor
1202-T	3M	Synthetic elastomer tape/scrim	Tape	By Hand	0.33 0.00118	Excellent	Non-hardening	Poor
XA-5367	3M	Oil Soluble elastomer (polybutene)	Ribbon	By hand	0.33 0.00118	Excellent	Non-hardening	Poor
801	3M	Polysulfide	Two Part 55/gal	Mix and pump	.69 .00246	Excellent	Tack Free 20 Hrs. cure-7 days	Poor
612	3M	Polysulfide	7 lb package	Pressure flow gun	.68 .00246	Excellent	Non-hardening putty	Poor

TABLE 15

Table 15 (Cont. Pg. 2)
General Survey of Sealant Compounds
and Manufacturers

Sealant	Manufacturer	Type	Form	Application	Cost/4x8 Panel Cost/Watt	Lifetime/ Weathering	Cure Time	Automation Potential
Scotch-Seal 5200	3M	Polyurethane	55 gal drum	Pressure flow gun	0.32 0.00114	Good	Tack free- 48 hrs cure-7 days	Poor
JA 3764	3M	Hot Melt	Cartridges	Hot Melt Extrusion	.36 .00128	Poor	45 Secs.	Fair
DC732	Dow Corning	1-part Silicone moisture cure	52 gal drum	Pressure flow gun	0.26 0.00094	Excellent	24 hrs	-
DC738	"	7-part silicone non- corrosive	4 1/2 gal pail	Pressure flow gun	0.51 0.00181	Excellent	24 hrs	-
DC790	"	Silicone construction sealant	-	-	-	Excellent	24 hrs	-
DC795	"	Silicone construction sealant	-	-	-	Excellent	24 hrs	-
DC3120	"	2-part silicone hi-temp	-	-	0.90 0.00321	Excellent	24 hrs	-
Eternaflex Hypalon sealant	Gibson-Homans	Hypalon	5 gal pails	Pressure flow gun	0.066 0.000236	Good	1-2 mo. for full cure	-
Eternaflex Neoprene sealant	"	Neoprene	Cartridges	Pressure flow gun	0.31* 0.00111	Good	1 week	-

TABLE 15 (cont.)

Table 15 (Cont. Pg. 3)
General Survey of Sealant Compounds
and Manufacturers

Sealant	Manufacturer	Type	Form	Application	Cost/4x8 Panel Cost/Watt	Lifetime/ Weathering	Cure Time	Automation Potential
Black rubber sealant	Woodhill Permatex	Neoprene	Cartridges	Pressure flow gun	0.055 0.006197	Good	2 hours	-
428	PRC	Polysulfide	Two part 55/gal	Mix and pump	.29 .00104	Excellent	16 hours	Poor
438	PRC	Polysulfide	Two part 55/gal	Mix and pump	.25 .00089	Excellent	16 hours	Poor
Macromelt 6238	Henkel	Hot Melt Polyamide Resin	25 lb. bag Pellets	Hot Melt Extrusion	.28 .00100	Poor	10 Sec.	Good
Versalon* 1140	"	Hot Melt Polyamid Resin	25 lb. bag Pellets	Hot Melt Extrusion	.34 .00121	Poor	10 Sec.	Good
Z12-069	Swift Adhesives	Hot Melt	Billets	Hot Melt Extrusion	.16 .00057	Fair	32 Sec.	Good
Z12-355	"	Hot Melt	Billets	Hot Melt Extrusion	.16 .00057	Fair	80 Sec.	Good
1200	G.E.	Silicone	5 gal pail	-	0.49 0.00175	Excellent	-	-
2400	G.E.	Silicone	5 gal pail	-	0.45 0.00161	Excellent	-	-
Silpruf	G.E.	Silicone	5 gal pail	-	0.48 0.00171	Excellent	-	-

TABLE 15 (cont.)

Table 15 (Cont. Pg. 4)

General Survey of Sealant Compounds
and Manufacturers

Sealant	Manufacturer	Type	Form	Application	Cost/4x8 Panel Cost/Watt	Lifetime/ Weathering	Cure Time	Automation Potential
RTV 103	G.E.	Silicone	5 gal pail	-	0.52 0.00186	Excellent	-	-
Dymeric	Tremco	3 part polyurethane	2 gal Container	-	0.25 0.000893	Good	-	-
THC900	"	2 part polyurethane	2 gal container	-	0.28 0.00101	Fair	-	-
Proglaze	"	Silicone	Cartridge	-	0.52 0.00185	Excellent	-	-
Butyl Sealant	"	Butyl	5 gal. drum	Pressure flow gun	0.14 0.000488	Excellent	Non-hardening	-
440 Tape	"	Butyl tape	Tape	-	0.44 0.00156	Excellent	Non-hardening	-
Mono	"	1 part Acrylic	2 gal container	Pressure flow gun	0.28 0.00102	Excellent	-	-
Acrylic Latex caulk	"	Acrylic latex	5 gal drum	Pressure flow gun	0.11 0.000377	Fair	1 hr.	-

TABLE 15 (cont.)

TABLE 16
Adhesive Bond Strength Evaluation^(a)

Notebook No.	Materials	Primer/ Adhesive	Control Value	Water Immersion 2 Weeks	Boiling Water 2 Hours
A11861-2A	Glass/EVA 9918	A11861	39.6	37.9	27.1
A11866-A	Glass/EVA 9918 w/blend	A11861	35.4	41.9	Cohesive
A11894-3	Galvanized/EVA 9918	A11861	2.5	NT	NT
A11894-4	Mild Steel/EVA 9918	A11861	56.0	42.6	50.7
A11895-1	Aluminum/EVA 9918	A11861	41.0	2.3	2.6
A11894-1	EVA 9918/Tedlar 100BG3OUT	A11861	4.5	NT	NT
A11894-2	EVA 9918/Korad 212	A11861	1.1	NT	NT
A12521-1	EVA 9918/Sunadex	A11861	34.8	Broke	32.3
A13881-1	EVA 9918/Tedlar 200BS30WH	68040	Cohesive, >20		
A13881-2	EVA 9918/Tedlar 200PT	68040	8.25		
A13881-3	EVA 9918/Tedlar 100BG3OUT	68040	6.14		
A13881-4	EMA 13439/Tedlar 100BG3OUT	68040	0.47	NT	NT
A13881-5	EMA 13439/Tedlar 200BS30WH	68040	1.88	NT	NT

(a) Average bond strength by ASTM D-903 or ASTM D1876.

TABLE 16

TABLE 17

Project No. 6072.1

RS/4 FLOURESCENT SUNLAMP EXPOSURE INVENTORY

Notebook No. /Mat'l/Cover	RS/4 No.	Start Date	Termination		Specimen Condition/Testing					
			Date	Hours	Color	Texture	%T	Modulus	Tensile	Elongation
A12505-1 EVA/5VinylTn	4	7/16/80	11/13/80	2880	ok	ok		437 psi	2020	595 %
formula A11873-1			3/13/81	5760	ok	ok		363 (100%)	1390	690%
A12505-2 EMA/ L 101			11/13/80	2880	ok	ok		-	374	36 %
formula A11868A	4	7/16/80	3/13/81	5760	ok	soft + sm. cracks		-	536	18%
A12505-3 EMA/ L-231	4	7/16/80	11/13/80	2880	ok	ok			332	27 %
formula A11868B			3/13/81	5760	ok	dec. cracks			478	35%
A12504-1 EMA	1	7/15/80	11/12/80	2880	ok	ok		669 psi	2680	640 %
formula A11877-fully compounded			3/13/81	5760	ok	ok		784 (100%)	3240	appx. 2000%
A12504-2 EMA, natural	1	7/15/80	11/12/80	2880	ok	ok		-	250	60 %
formula 2205			3/13/81	5760	ok	ok		broken	-----	broken

TABLE 17

TABLE 17 - (Cont. page 2)

Project No. 6072.1

RS/4 FLOURESCENT SUNLAMP EXPOSURE INVENTORY

Notebook No. /Mat'l/Cover	RS/4 No.	Start Date	Termination		Specimen Condition/Testing					
			Date	Hours	Color	Texture	%T	Modulus	Tensile	Elongation
A12504-3 EVA	1	7/15/80	11/12/80	2880	ok	ok		252 psi	1930	631 %
formula A9918			3/13/81	5760	ok	ok		305 (100%)	1340	550
fully compounded										
A12504-4 3M acrylic	4	7/16/80	11/13/80	2880	ok	ok		-	16,100	7%
film no. PF7430300			3/13/81	5760	ok	ok		-	8,350	appx. 1%

TABLE 17 (cont.)

TABLE 18

DIFFERENTIAL THERMAL ANALYSIS

(10°C/min. Rise)

Compounds	Number/Type	Atmosphere	Major Peaks, C°	
			1st	2nd
Elvax 150	Base Resin	Air	220	430
		Nitrogen	340	450
EVA	A9913 compound cured	Air	227	425
		Nitrogen	310	450
EPDM	A8945A compound cured	Air	210	310
		Nitrogen	-	450
PVB	"Saflex PT-10"	Air	175	240
		Nitrogen	-	365
Silicone	Sylgard 184 cured	Air	-	300
		Nitrogen	nothing to 500	
EMA	2205, base resin	Air	215	408
		Nitrogen	-	420
EMA	A11877 compound cured	Air	212	384
		Nitrogen	-	430
BA	A12550, butyl acrylate, cured	Air	207	388
		Nitrogen	206	383

TABLE 19
Anti-Soiling Test Results

(%I_{SC})

Change in Short Circuit Current w/Standard Cell

Treatment	%I _{SC} Sunadex (Plain)			A. Δ	%I _{SC} X-22417 On Glass			B. Δ	%I _{SC} Tedlar 100BG30UT On Glass			C. Δ
	0	1	2		0	1	2		0	1	2	
None	90.5	89.0	88.7	-1.8	84.0	80.9	80.7	-3.3	87.7	85.3	84.8	-2.9
L-1668	89.7	89.9	88.6	-1.1	80.3	79.5	80.0	-0.3	88.4	86.9	87.1	-1.3
Ozone, Then L-1668	-	-	-	-	84.5	81.6	82.4	-2.1	88.1	87.4	87.3	-0.8
E-3820-103B	90.0	89.9	89.9	-0.1	80.0	78.5	78.7	-1.3	86.0	86.5	86.0	0
Ozone, Then E-3829-103B	-	-	-	-	84.1	83.3	82.4	-1.7	86.0	82.8	83.5	-2.5
OI-650 Glass Resin	91.0	90.5	89.6	-1.4	81.1	79.3	78.9	-2.2	89.0	86.3	86.4	-2.6
SHC-1000	91.9	89.6	89.4	-2.5	82.1	78.0	77.8	-4.3	89.0	86.5	86.9	-2.1
WL-81 Rohm & Haas	90.7	88.0	88.7	-2.0	83.6	81.0	80.7	-2.9	87.7	86.5	84.8	-2.9

Legend: 0 = Control Value, No Exposure
1 = Value After One Month Exposure Outdoors
2 = Value After Two Months Exposure Outdoors
Δ = % Change Over Control Value

TABLE 19

TABLE 20

Anti-Soiling Test Results

% T

Change in Total Integrated Transmission

Treatment	%T Sunadex (Plain)			A. Δ	%T X-22417 On Glass			B. Δ	%T Tedlar 100BG3OUT On Glass			C. Δ
	0	1	2		0	1	2		0	1	2	
None	93.1	92.6	92.8	-0.3	90.0	90.7	90.2	+0.2	90.9	91.3	90.9	0
L-1668	93.1	92.7	92.8	-0.3	90.1	90.0	89.9	-0.2	91.1	91.0	91.0	0
Ozone, Then L-1668	-	-	-	-	90.4	90.7	90.4	0	90.7	86.2	91.1	+0.4
E-3820-103B	97.2	92.5	92.7	-4.5	90.0	89.7	90.0	0	91.0	90.8	91.0	0
Ozone, Then E-3820-103B	-	-	-	-	92.2	89.7	90.3	-1.9	93.0	90.9	90.5	-2.5
OI-650 Glass Resin	93.0	92.6	92.6	-0.4	90.1	90.7	90.1	0	90.8	91.3	90.8	0
SHC-1000	93.2	92.8	92.6	-0.6	90.6	93.0	90.0	-0.6	91.1	91.2	91.0	-0.1
WL-81 Rohm & Haas	93.4	92.5	92.7	-0.7	90.7	90.7	90.1	-0.6	91.7	91.1	91.0	-0.7

Legend: 0 = Control Value, No Exposure
 1 = Value After One Month Exposure Outdoors
 2 = Value After Two Months Exposure Outdoors
 Δ = % Change After Last Exposure Period

TABLE 20

TABLE 21

Anti-Soiling Treatment Evaluation
Ion Plated and "Liquid Glass" Coated Specimens

Change in Short Circuit (I_{sc}) w/Standard Cell

Material & Coating	0	1	2	Δ
Magnesium Fluoride Ion Plated Glass	88.3	87.5	86.5	-1.8
Untreated Glass Blank	78.8	78.1	78.1	-0.7
Chromium Phosphate Coated Glass	71.8	70.2	69.9	-1.9
Iron Phosphate Coated Glass	74.9	72.8	72.7	-2.2
Uncoated Acrylic Blank	90.9	90.4	89.7	-1.2
Iron Phosphate Coated Acrylic	88.5	87.1	88.3	-0.2
Titanium Dioxide Coated Acrylic	90.5	89.3	89.5	-1.0

Change in Total Integrated Transmission (%T)

Material & Coating	0	1	2	Δ
Magnesium Fluoride Ion Plated Glass	91.6	91.6	92.4	+0.8
Untreated Glass Blank	90.9	91.1	91.1	-0.2
Chromium Phosphate Coated Glass	88.8	89.2	89.4	+0.6
Iron Phosphate Coated Glass	89.8	90.1	90.4	-0.6
Uncoated Acrylic Blank	92.1	91.9	91.8	-0.3
Iron Phosphate Coated Acrylic	91.2	91.8	91.7	+0.5
Titanium Dioxide Coated Acrylic	92.0	91.9	91.7	-0.3

Legend: 0 = Control Value, No Exposure
 1 = Value After One Month Outdoor Exposure
 2 = Value After Two Months Outdoor Exposure
 Δ = % Change of Last Measurement to Control Value

TABLE 22
CORROSION MONITORING

TEST SPECIMENS			CORROSION CONDITIONS					
Notebook No.	Materials	Primer	HOURS-ASTM B-117 Salt Spray					
			24	120	300	450	700	1600
A11867-A	Galvanized Steel	A11861-1	1	1	2	3	5	6
A11867-B	Mild Steel	A11861-1	1	2	4	4	4	4
A11867-C	Copper	A11861-1	1	1	1	1	1	1
A11867-D	Aluminum	A11861-1	1	1	1	1	1	1
A11880-2	Glass/EVA/Al module Al	A11861-1	1	1	1	1	1	1
A11880-2	Glass/EVA/Al module Cu	A11861-1	1	1	1	1	1	1
A11880-2	Glass/EVA/Al module Fe	A11861-1	1	1	1	1	1	1
A11880-2	Glass/EVA/Al module (Galvanized)	A11861-1	1	1	1	1	1	1
A11880-1	Glass/EVA/Al module Al	Unprimed	1	1	1	1	1	1
A11880-1	Glass/EVA/Al module Cu	-	1	1	1	1	1	1
A11880-1	Glass/EVA/Al module Fe	-	1	1	1	1	2	4
A11880-1	Glass/EVA/Al module (Galvanized)	-	1	1	1	1	1	1

Legend:

- | | |
|---|---|
| 1. Unaffected | 6. Heavy corrosion visible
(over 20% of surface) |
| 2. Slight dulling of surface | 7. Discoloration of polymer |
| 3. Noticable dulling of surface | 8. Delamination at interface |
| 4. Light corrosion visible | 9. No measurable current |
| 5. Medium corrosion visible
(10% of surface) | |

TABLE 23

Hardboard Protection Attempts

Hardboard Treatment	Average Measurement	% Change From Initial After 2 Days, 25°C 100% RH	% Change From Initial After Vacuum Bag Cycle	% Change From Initial After re-equilibration 2 Days/25°C/30%RH
None, control	Inner thickness	+1.13	-1.21	-0.35
Equilibrated to 37% RH/25°C	Outer thickness	+0.69	-2.29	-2.06
	Width	+0.15	-0.18	-0.04
	Length	+0.10	-0.15	-0.03
	Weight	+1.70	-2.77	-0.54
Both surfaces coated with Korad film, M6112 adhesive	Inner thickness	+0.94	-1.59	-1.36
Equilibrated to 37% RH/25°C	Outer thickness	+0.45	-3.62	-3.17
	Width	+0.11	-0.12	-0.11
	Length	+0.11	-0.11	-0.10
	Weight	+1.00	-2.28	-1.88
Surfaces open, edges sealed with epoxy cement	Inner thickness		-4.87	
Equilibrated at 100% RH, 23°C	Outer thickness		-3.69	
2 weeks	Width		-0.77	
	Length		-0.52	
	Weight		-6.32	
Surfaces open, edges sealed with epoxy cement	Inner thickness		-3.15	
Equilibrated at 50% RH, 25°C for 2 weeks	Outer thickness		-2.48	
	Width		-0.25	
	Length		-0.21	
	Weight		-4.17	

TABLE 23
(continued)

Hardboard Protection Attempts

<u>Hardboard Treatment</u>	<u>Average Measurement</u>	<u>% Change From Initial After 2 Days, 25°C 100% RH</u>	<u>% Change From Initial After Vacuum Bag Cycle</u>	<u>% Change From Initial After re-equilibration 2 Days/25°C/30%RH</u>
Surfaces sealed with Korad film, edges sealed with epoxy cement, Equilibrated at <u>100% RH/25°C</u> for 2 weeks	Inner thickness Outer thickness Width Length Weight		-5.34 -3.58 -0.41 -0.47 -6.78	
Surfaces sealed with Korad film, edges sealed with epoxy cement, Equilibrated at <u>50% RH/25°C</u> for 2 weeks	Inner thickness Outer thickness Width Length Weight		-2.62 -2.34 -0.14 -0.18 -3.04	

TABLE 24
Hardboard Protection Experiments

Notebook No.	11"x11" Hardboard Treatment	Temp/RH Equilibration Fair to Sealing	Total % Wt. Loss (Whole Module)	% Wt. Loss w/Respect To Hardboard Only
13876-1	Sealed in Aluminum Foil w/3M 4910 Adhesive	25°C/60%	3.9%	4.6%
13876-2C	Sealed in EMA A13439 and Tedlar 200 PT w/68040 Adhesive-1 min. press @ 150°C	25°C/60% RH	1.8%	2.2%
13877-3	Sealed in EVA A9918 and Tedlar 200 PT w/68040 Adhesive-1 min. press @ 150°C	25°C/60% RH	2.3%	2.9%
13879-4	Sealed first w/foil and 3M 4910 Adhesive. Foil was primed with All801 Primer and Sealed with EMA A13439 and Tedlar 200 PT w/68040, 1 min. press @ 150°C	25°C/60% RH	1.3%	1.9%
13880-5	Sealed same as 13079-4	24°C/100% RH	4.4%	6.4%
14301-1	3M-4910 Adhesive w/2 mil T302 Stainless Steel Foil-Wrap Around	23°C/55% RH	2.85%	4.17%
14301-2	EVA 9918 with 2 mil T302 Stainless Foil-Wrap Around	23°C/55% RH	1.88%	3.13%
	Control	26°C/70% RH	4.81%	4.81%

TABLE 24

EXPERIMENTAL DOUBLE VACUUM BAG ASSEMBLY

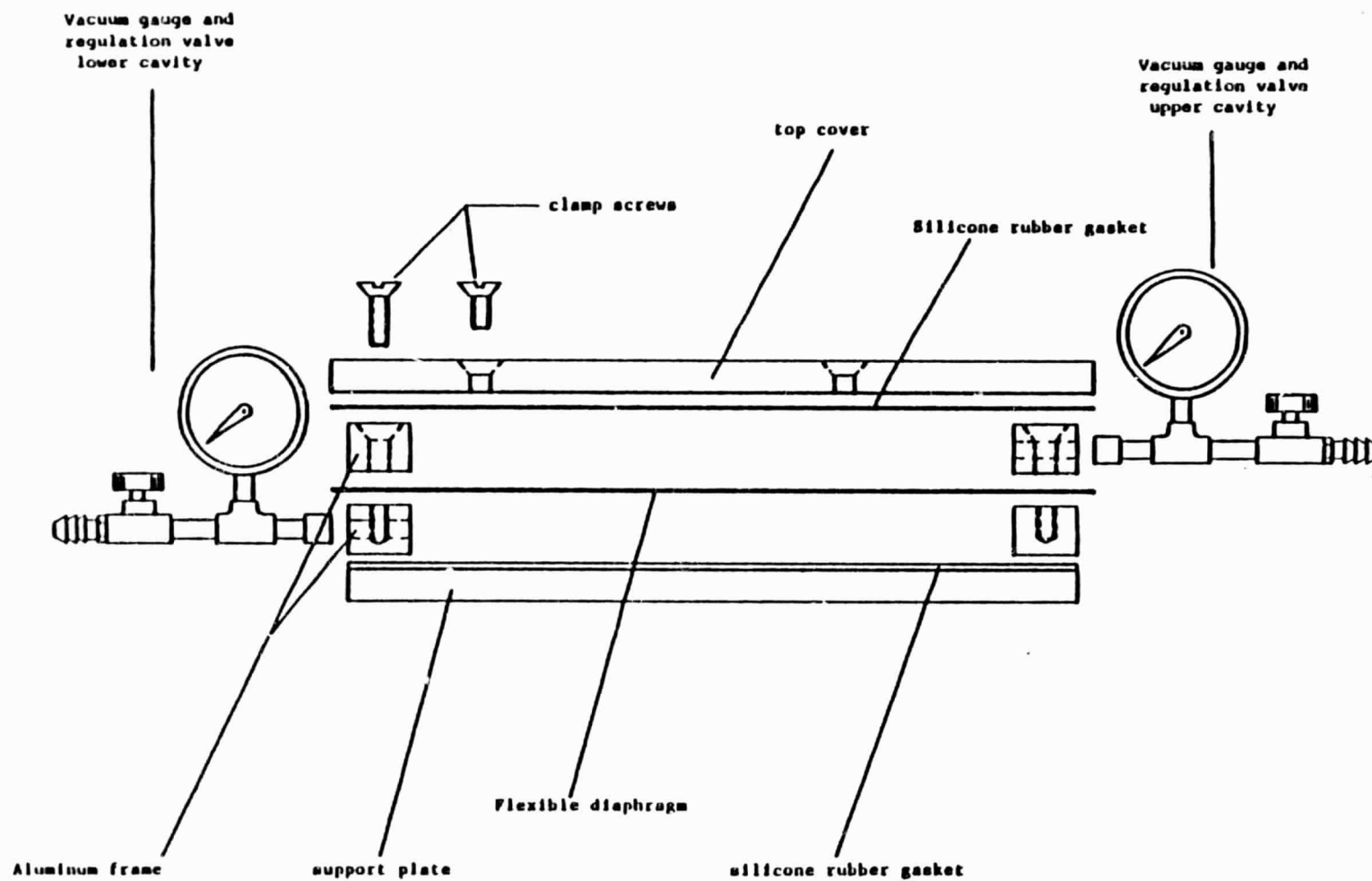
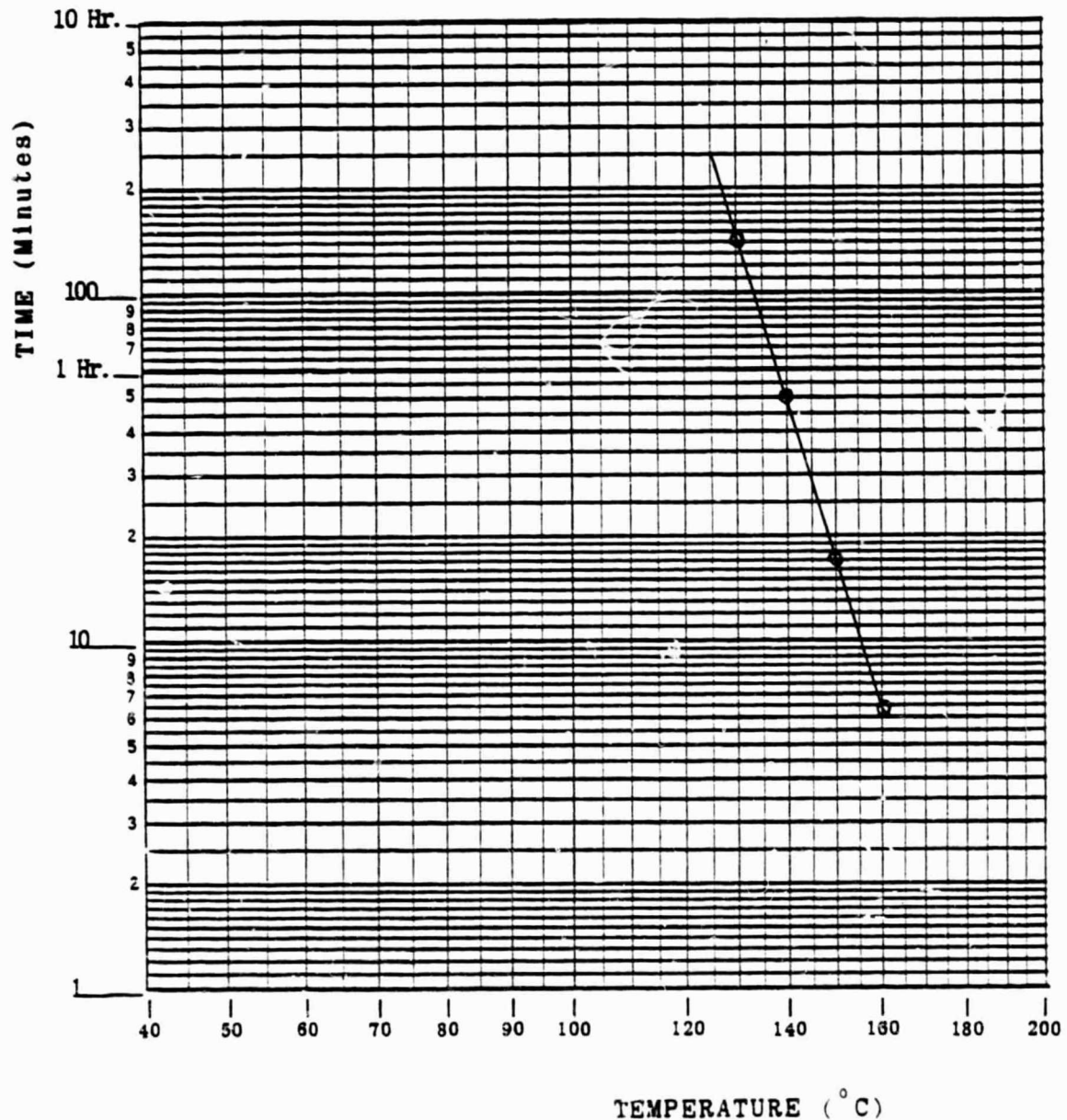


Figure 1

Figure 2

EVA Cure Curve:
Peroxide Half - Life Temperature Graph (a)



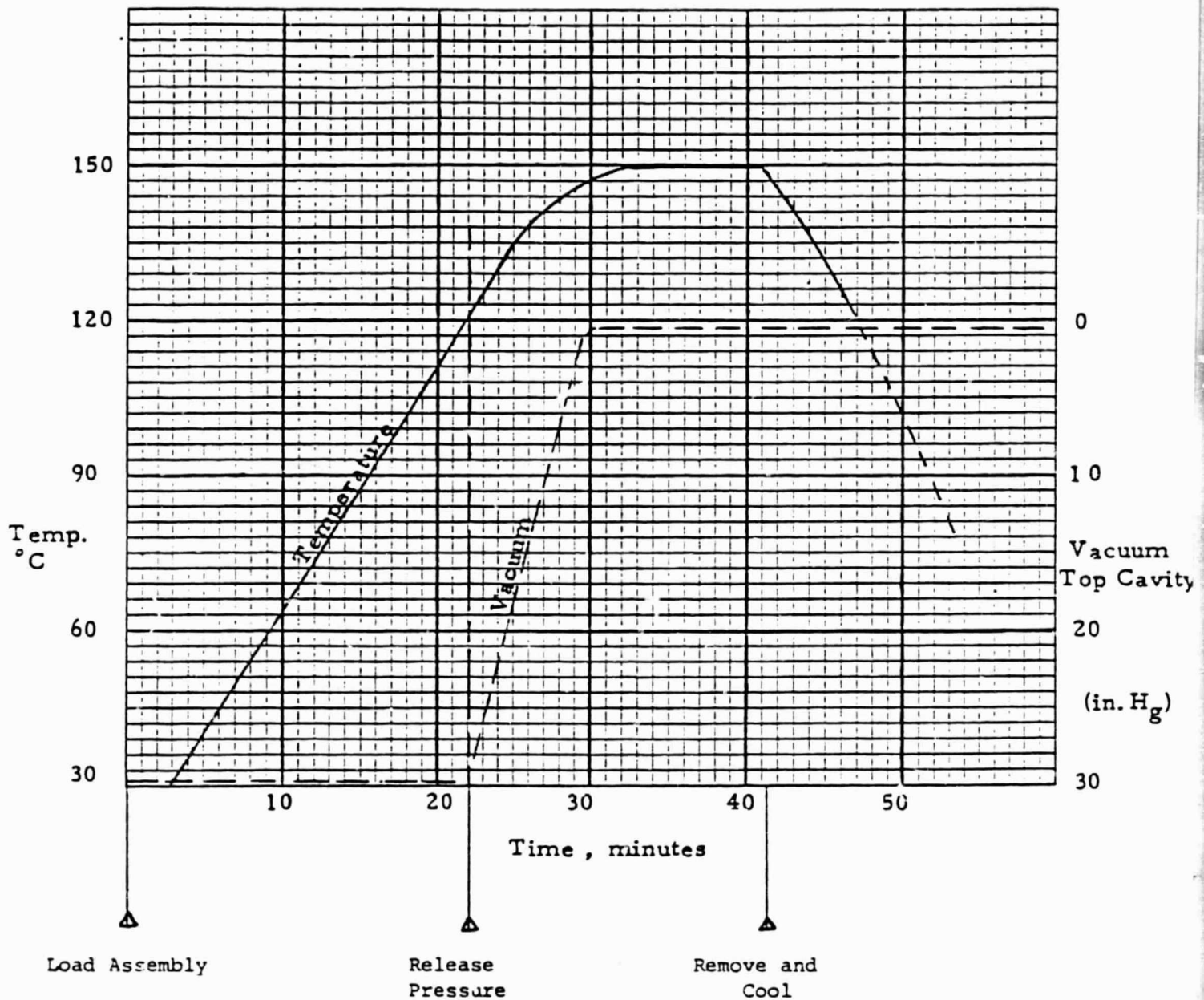
(a) For Lupersol 101 peroxide; 2, 5-Dimethyl-2, 5-di(t-butyl peroxy)hexane

Source: "Evaluation of Organic Peroxides from Half-Life Data"
Bulletin 30-30; Lucidol Division, Pennwalt Corporation,
Buffalo, New York

Note: No cure of the EVA pottant occurs below 125°C.

Figure 3

MODULE FABRICATION
TIME / TEMPERATURE / PRESSURE CYCLE



1. Load preassembled module into vacuum fixture and pump both cavities down to 30 in. Hg for at least 5 minutes.
2. Load into preheated platen press to heat module at approximate rate of 4°C/min. Both cavities are kept under full vacuum.
3. At a temperature of 120°C the pressure of the upper cavity is gradually released and permitted to come to room pressure over an 8 to 10 minute period.
4. The assembly is left in the press for 10 minutes after a temperature of 150°C has been reached, then removed with the lower cavity still under evacuation.
5. The module is removed from the vacuum bag after cooling for approximately 10 minutes.

FIGURE 4

PRODUCTION FLOW CHART

BUTYL ACRYLATE SYRUP
REVISED, FORMULA NO. A12805

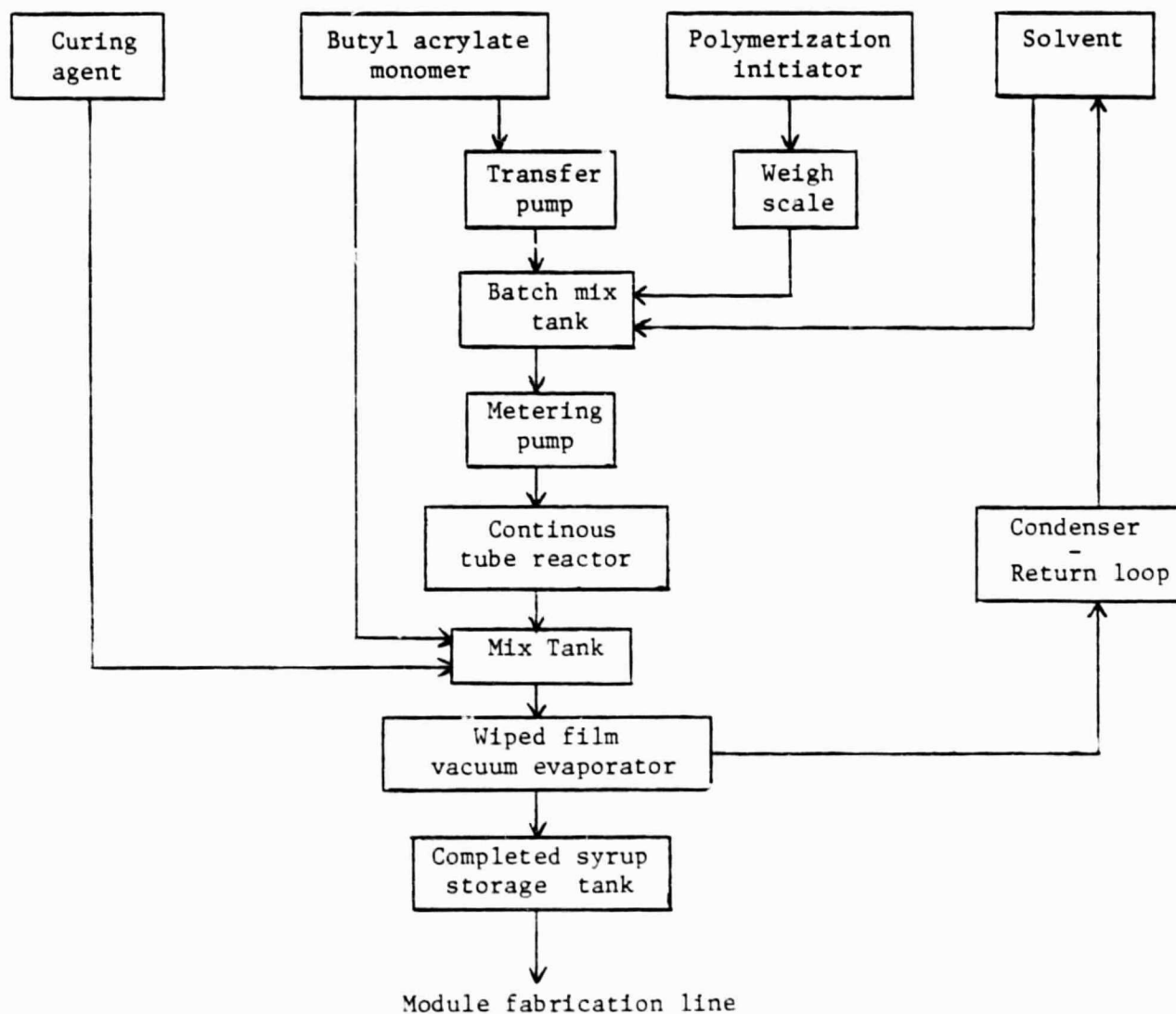
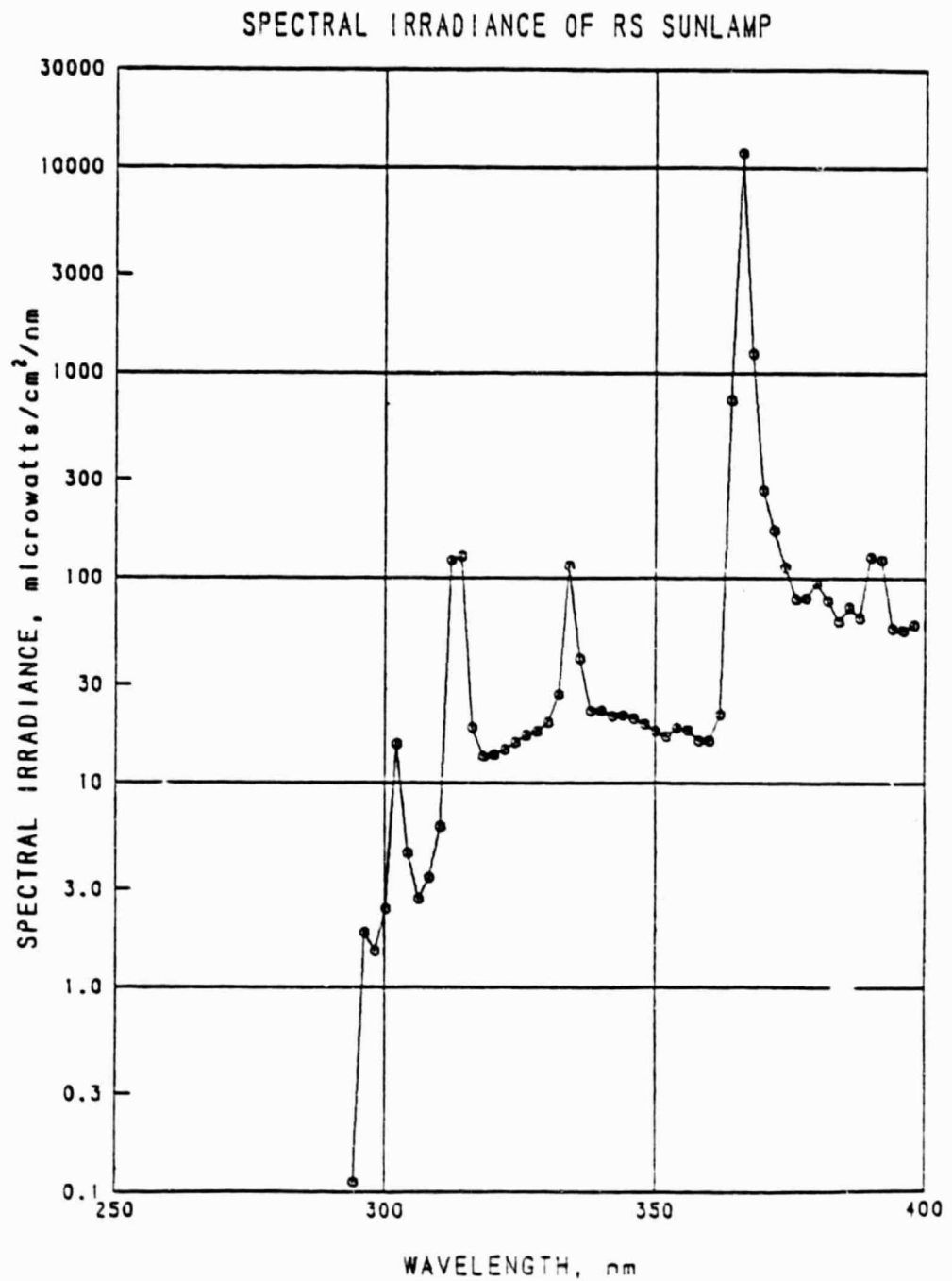


Figure 5



Estey, Roger S., "Measurement of Carbon Arc and Sunlamp Sources at Dow Corning and Springborn Laboratories" Jet Propulsion Laboratory, IOM [REDACTED]